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Does time perception underlie delay discounting?

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Does time perception underlie delay discounting?

by

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Does time perception underlie delay discounting?

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Abstract. Delay discounting, the belief that rewards decline in value over time, is a phenomenon observed in several clinical disorders, including Attention Deficit / Hyperactivity Disorder (ADHD), substance abuse disorders, and other impulse control disorders. Delay discounting behavior is characterized by a tendency to choose smaller, more immediate rewards over larger, more delayed rewards. This tendency has been associated with behavioral impulsivity and inability to delay gratification observed in the aforementioned clinical disorders.

It has been suggested that time perception may be a salient feature of delay discounting. If the larger, longer-term reward is perceived as being more temporally remote, its relative value decreases and is associated with greater cost, and one becomes more likely to choose the more immediate reward over the longer-term (though optimal) choice. Time perception has been studied in clinical populations, with increased variability of responses as well as both under-production and overestimation of time intervals observed in those with ADHD and other disorders

associated with impulsivity.

The present study used informational feedback via a metronome to change belief regarding duration of a second- either increasing or decreasing it by approximately 20%. Participants were 132 college-aged students with and without a diagnosis of ADHD. Measures of impulsivity and ADHD symptomatology were collected as well, and participants completed several cognitive tasks measuring working memory and processing speed to explore the impacts of these measures on delay discounting and time perception. While participants were able to reliably incorporate the altered second belief into short estimations of time (i.e., less than a minute), the manipulation failed to generalize to longer-duration temporal estimations, and it did not affect delay discounting. Neither ADHD symptomatology, impulsivity, nor performance on the cognitive tasks were related to delay discounting behaviors, though a working memory measure was correlated with baseline (pre-manipulation) time and one longer duration estimation. This lends support to a relationship between working memory and temporal perception, though the relationship between temporal perception and delay discounting remains elusive. Directions for future studies to clarify the role of temporal processing and ADHD in delay discounting are discussed.

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Chapter 1: Introduction

Delay discounting is a widely studied tendency to prefer smaller, sooner rewards over larger, later rewards (Kirby & Marakovic, 1996). For example, if one is offered the choice of receiving $20 or $25 with no strings attached, right now, nearly everyone would choose the $25. However, if we alter the scenario to offering $20 right now, or $25 in three months, many people will choose the $20 now despite the fact that the $25 has greater monetary value. What has changed? In this case, the future reward has been devalued with respect to the present reward- its subjective value has decreased as the variable of time has been introduced. However, not all people will respond to this scenario in the same way.

Some studies have found that people that exhibit greater levels of certain aspects of impulsivity, especially those with clinical disorders such as substance abuse/dependence disorders (e.g., addictions to nicotine, alcohol, cocaine, etc), attention-deficit/hyperactivity disorder (ADHD), and other impulse control disorders, tend to devalue future rewards at a steeper rate than those exhibiting lower levels of impulsivity (e.g., Reynolds, 2006; Scheres, Lee, & Sumiya, 2007; Green & Myerson, 2004). For these individuals, the future reward appears to lose value much faster than for a non-impulsive individual. The basis for this preference for the sooner reward, even as its monetary value is lowered, is not well understood.

At this time, the relationship between impulsivity and delay discounting is not clear. Because the valuation of rewards changes as a function of time, it may

stand to reason that there may be some temporal aspect that at least partly underlies the phenomenon of delay discounting. Research supports the hypothesis that impulsivity is related to differential temporal processing, with the finding that greater impulsivity is associated with over-estimation of time durations and under-production of time intervals (e.g. Berlin & Rolls, 2004; Glicksohn et al., 2006). For example, in the over-estimation of time intervals, an actual 10-second interval is estimated to have lasted 12 seconds. An example of under-production of a time interval would be when asked to tap when 10 seconds have gone by, the individual instead taps after only 8 seconds, having believed the interval was longer. Thus they have under-produced the desired time interval.

Previous studies have examined the correlations between impulsivity, time perception, and delay discounting, but these studies have not explored possible causal links that may exist between these variables. In order to investigate whether a difference in temporal processing causes differential rates of delay discounting, an experimental manipulation is warranted. The present study manipulates an aspect of time perception by using an altered metronome that provided false feedback to convince the participant a second is longer or shorter than it is. This study then examines if this manipulation affects rates of delay discounting. Comparison of results within and between a normative group and an ADHD group allows us to attempt to clarify the nature of the relationship between impulsivity in and out of

the context of ADHD, and susceptibility to the manipulation and its effects on delay discounting.

Additionally, there are several other cognitive processes whose relationships with temporally myopic decision-making (delay discounting) have not been thoroughly examined. To further understand what factors may underlie the complex behavior involved with delay discounting, it is worthwhile to examine other factors that may be possibly associated with delay discounting, including working memory and processing speed. These factors are important to examine because as outlined previously, delay discounting has been found to correlate with measures of impulsivity; this is coupled with the finding that decreased performance on measures of working memory and processing speed have also been correlated with higher impulsivity, including in clinical populations with ADHD and other impulse control disorders (Finn et al., 1999). Because degree of delay discounting has been correlated with both intelligence and impulsivity (see section 2.2), examining specific processes that are shared by both may further clarify what aspects of cognition underlie this type of decision-making.

Specifically, the objectives of the present study are the following: 1. To examine how feedback from a device regarding the length of a second can influence explicit temporal duration estimations; 2. To determine if this local manipulation of temporal perception affects rates of delay discounting; 3. To examine how

manipulation of temporal perception affects an ADHD population's delay discounting rates; 4. To examine how self-reported impulsivity may moderate the effects of time perception on delay discounting; 5. To examine how processing speed and working memory may affect delay discounting.

It is hypothesized that 1. feedback and training to a false metronome will affect time interval estimates, with exposure and training to 50 beats per minute (bpm), but labeled as 60 bpm / 1 beat per second, inducing under-estimations of time intervals. Exposure and training to 70 bpm (labeled also as 60 bpm / 1 beat per second) will induce over-estimations of time intervals. 2. Those who have been exposed to the slow tempo (50 bpm) will show decreased rates of delay discounting in a delay discounting task; those exposed to the fast tempo (70 bpm) will show increased rates of delay discounting. 3. The ADHD group will exhibit results similar to the non-ADHD group, but with a smaller effect size due to inherent greater variability of time perception. 4. Higher levels of trait impulsivity in all groups will be associated with higher rates of delay discounting. 5. Slower processing speed and decreased working memory capacity will be associated with higher rates of delay discounting.

The remainder of this document is structured as follows. The background and previous review section (Chapter 2) defines and gives a review of the delay discounting literature, a review of time perception and impulsivity research, and how these are explicitly expressed in normal populations and those with ADHD.

Chapter 3 will discuss in more depth the current study's aims and hypotheses. Chapter 4 details the methodology and materials of the current study. Chapter 5 presents the results of the current study, and Chapter 6 is a discussion of those results.

Chapter 2: Background and Previous Work

The purpose of this section is to provide a contextual understanding of the topics discussed and examined in this study, and to operationally define the terms used throughout.

2.1 Delay Discounting

What is Delay Discounting?

As previously mentioned, delay discounting (also referred to in the literature as temporal discounting, time discounting, and hyperbolic discounting) is a tendency to assign lower value to an outcome or reward because of its location in the future. Stated succinctly, the general rule is "the sooner, the better" (Kirby & Marakovic, 1996). Delay discounting may manifest both as the tendency to choose a reward now to one of equal objective value later in time (e.g. $10 now vs. $10 in a month), or the tendency to choose an objectively *smaller* reward now to a larger reward later in time (e.g. $10 now vs. $15 in a month). In this paper, primarily the second distinction will be addressed as it more realistically reflects the variance of choices present in day-to-day lives- it is difficult to equalize non-monetary choices.

Though most commonly associated with monetary reward choices, which are secondary reinforcers, similar delay discounting behaviors occur with primary rewards, such as with juice (McClure et al., 2007). Delay discounting has also been observed in non-human primates, with findings that rhesus monkeys delay discount

saccharine administration in a similar way to human's behavior with money and juice (Freeman et al., 2009). It has been observed when the intertemporal interval is as short as seconds (Gregorios-Pippas et al., 2009) and as long as many years.

What is the Importance of Delay Discounting?

Delay discounting permeates our lives at many junctures. In one form, it may manifest itself as deciding to put off a bill one month and instead using the money for other pursuits, even though when the bill arrives next month it will include a late fee. Another example would be a recent graduate refusing to put away money toward retirement- the time that will elapse before the money can be enjoyed feels impossibly long and it is felt that the money is better spent in the here and now, enjoying youth. Beyond the realm of money, delay discounting can have other significant impacts: the child with ADHD spends the night playing video games rather than studying for an exam, as the immediate value of playing the game is perceived as greater than studying now and doing well on the next day's exam. Or perhaps the heroin addict chooses to take another pleasurable hit at the expense of living a healthy, longer life.

The above are all negative consequences of varying severity to delay discounting. If the outcomes are suboptimal, how can it be that this behavior pattern has been preserved in our species? It may be that a tendency toward delay discounting offers security in the present at the expense of security in the future,

and our species (like any other) is largely concerned with furthering a genetic line rather than an individual living long into the future. Nevertheless, delay discounting is largely maladaptive, associated with numerous negative outcomes, including drug dependence (see Reynolds, 2006, for review), obesity (Weller et al., 2008), and pathological gambling (Alessi & Petry, 2003). Greater understanding into this phenomenon may enable us to better understand and treat clinical outcomes associated with it.

How can we Characterize Delay Discounting?

Delay discounting can be characterized by the *indifference point*, the point at which a present option is equally preferred to a future option. Both options, present and future, have the same subjective value to the participant. For example, Person A equally prefers to receive $20 today or $100 a year from today. We can say the indifference point for $100 in a year for person A is $20. Another participant, Person B, equally prefers $80 today when compared with $100 in the future. Person B's indifference point for $100 in the future would be $80. In this example, person A is exhibiting a steeper decline in value assigned to his future rewards- this would be increased delay-discounting. Person B is exhibiting a relatively more shallow decline in value- though is still exhibiting delay discounting, albiet at a decreased rate when compared with person A.

The "steepness" of delay discounting can be described mathematically as a hyperbolic (rather than exponential) curve with the following equation:

$$V = \frac{A}{1 + kD}$$

where *A* is the objective value or magnitude of a delayed reward, *V* is the current subjective value of that reward, *D* is the delay to delivery of the reward, and *k* is a free parameter that describes the "steepness" of the discounting curve (Kirby, 1997). A high *k* value would represent greater rates of delay discounting, typified by person A. A lower *k* value would describe lower rates of delay discounting (but still delay discounting), typified by person B. For illustrative purposes, two sample hyperbolic discounting curves are shown below, one steep and one shallow (adapted from Coffey et al., 2003):

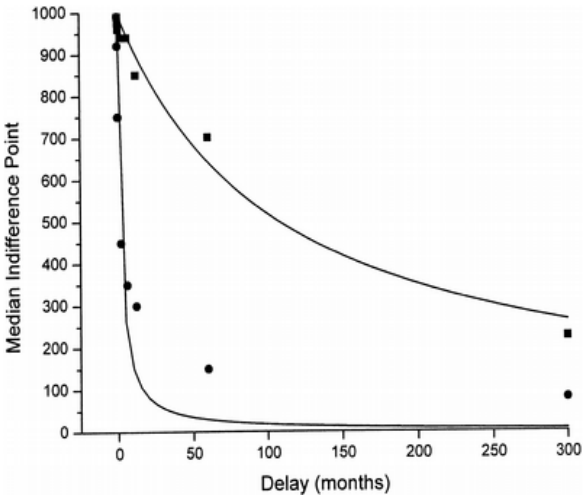


Figure 1: Two hypothetical delay discounting curves depicting how the relative value of an object measured by the indifference point (the point that two objects of different objective value are viewed as subjectively equal) changes over time. The leftmost curve is steep, corresponding to a higher *k* value, while the rightmost curve is much more shallow, corresponding to a lower *k* value.

Over time, people's delay discounting curves flatten: as time extends outwards, the delay discounting curve becomes more shallow. Kirby (1997) describes this hyperbolic curve as "an attenuation in rate of devaluation with increasing delay: value is discounted most precipitously over relatively short delays but moderates as delay length increases." For example, something that is perceived to be worth $100 a year from now will be perceived to be roughly worth the same a year and a day from now and preferences to receive the money in a year or a year and a day will not be strongly differentiated- there will be greater indifference for either option. Compare this with the option of receiving $100 today vs. $100 tomorrow. Though the difference in time is the same (1 day), the preference will be much stronger in comparing today with tomorrow as the decline curve in subjective value, *k*, is steeper per unit of time in the near future when compared with the further future (Thaler, 1981).

It is important to note that the delay discounting curve for an individual is not fixed; it has been shown to vary in response to various internal and external manipulations. For example, a repeated-measures study found that participants exhibited much steeper delay discounting curves when they were deprived of sleep versus having adequate sleep (Reynolds & Schiffenbauer, 2004). Though often thought of as a trait measure, it is perhaps more accurate to consider it a state-measure. Neurobiological evidence exists that differential brain regions are

activated as delay discounting curves shift both within and between subjects (e.g., review by Peters & Buchel, 2011).

Neurobiological Correlates.

Currently, there is relatively little work that has examined the neurobiological substrates that underlie delay discounting, considering its role in suboptimal human behavior. An article by Monterosso et al. (2006) reviews some of the important findings. Several structural studies have found that the ventromedial prefrontal cortex (mPFC), including the orbitofrontal cortex (OFC), plays a role in determining the subjective value of delayed rewards (Bechera, Damasio & Damasio, 1994). Specifically, lesion studies have shown that patients with mPFC lesions show difficulties with decision making, and have been described as having a strong preference to choose immediate rewards rather than invest in future rewards (Bechara et al., 1996, 1999). Animal studies also support the role of the OFC in delay discounting. OFC lesions in rats produce greater preference for smaller immediate rewards over larger future rewards (Mobini et al., 2002).

McClure et al. (2004) conducted the first functional magnetic resonance imaging (fMRI) study of delay discounting. This study found that activation during temporal decision making favoring delayed rewards was greater in lateral prefrontal and posterior parietal cortices. Conversely, the corticolimbic system was activated by immediate reward opportunities. These results were replicated when the reward

was juice rather than money (McClure 2007). A similar study examined delay discounting in cocaine addicts and demonstrated diminished activation of mPFC and ventral striatum in general reward processing, coupled with behavioral preferences for the smaller, sooner reward (Potenza, 2008).

A functional magnetic resonance imaging (fMRI) study by Kable and Glimcher (2007) found evidence that the subjective value of delayed rewards is represented explicitly in several brain regions. In this study of 10 normative participants, increased activation of ventral striatum, mPFC, and posterior cingulate cortex was associated with both objective increase of reward, and, importantly, choosing the delayed choice when it was perceived as more valuable. Decreased activation of these areas was observed when the delay to the reward increased. A follow-up study by the same authors found increased ventral striatal, mPFC, and medial OFC (mOFC) activation when participants favored the smaller immediate reward, while choice of the delayed reward was associated with greater lateral OFC and lateral PFC activations. These brain areas have previously been implicated in the reward-processing stages of decision making (Rogers et al., 2004).

A study by Wittmann et al. (2007) supports this finding that differential brain regions are activated in response to choosing long or short term rewards: in a hypothetical delay discounting task, activation of striatum, specifically the caudate and putamen, covaried positively with perceived delay of reward, with amount of

activation coding for delay of reward. This, however, is somewhat at odds with other studies implicating greater striatal activation with smaller delays.

A study by Tanaka et al. (2004) found differential activation of the striatum and insula depending on the behavior strategy participants learned in response to a delay discounting task. Specifically, they found that when participants learned to select the smaller, immediate reward, ventroanterior regions of the above structures and lateral OFC regions showed increased activation. This is contrasted with greater dorsoposterior activation of the striatum and insula when participants learned to delay gratification and choose the delayed option. In addition, when choosing the larger delayed reward, dorsolateral PFC, inferior parietal cortex, the dorsal raphe nucleus, and the cerebellum were also activated. Based on these results, they hypothesized that ventroanterior regions of the striatum and insula are recruited for short-term reward prediction, and the dorsoposterior regions implicated in long-term reward prediction.

In short, these fMRI findings indicate distinct neuronal activation when participants choose immediate or delayed rewards in a delay discounting task. Greater medial, striatal, limbic and paralimbic activation is observed when participants favor the short-term reward, while greater lateral, parietal and prefrontal cortical activation was associated with the executive control activated when participants were able to or learned to choose the delayed choice (Wittmann, 2007).

There is also evidence for white matter differences that may contribute to delay discounting behavior. A diffusion tensor imaging (DTI) study by Olson et al. (2009) found that less impulsive decision making on a delay discounting task (i.e. more often choosing the optimal delayed reward choice) in a normative sample of 9-23 year olds was associated with higher fractional anisotropy and lower mean diffusivity of white matter tracts in bilateral frontal and temporal lobes. Fractional anisotropy is thought to reflect white matter density, axonal diameter, and myelination; in combination with mean diffusivity it can be used to predict the integrity of various brain structures. The results of this study indicate better white matter integrity is associated with more optimal decision making, at least in the ages studied.

Economic and Psychological Theories of Delay Discounting

Like any human behavior, the underlying variables that drive delay discounting are likely to be many. Most studies examining delay discounting have focused on characterizing the phenomenon rather than exploring its causal roots. However, there have been several studies that have attempted to answer the question of what underlies delay discounting.

There have been several economic theories put forth by researchers to explain the delay discounting phenomenon. One theory we can call the interest theory, is the belief that the rewards taken immediately may increase in value over time, and eventually overtake the value it would have offered if taken in the future (Frederick et al., 2002). In other words, $100 received today could somehow gain interest, via some mechanism like investment, and ultimately be worth more than $100 in the future. However, it is unclear how this mechanism could account for the similar delay discounting curves observed in non-monetary reward paradigms, such as with juice; or in non-humans that presumably cannot account for this type of interest.

Similarly, there may be a belief that money offered in the future may be worth less than it is now, due to inflation, a tendency for a unit of currency to devalue with time. However, this also would not fully explain delay discounting for the same reasons the interest theory would not. Because delay discounting has been observed on the order of seconds and minutes, it would seem unlikely to assume that money could devalue on such a small time scale. This does not, however, rule out a more broad belief in the uncertainty of the future. People may fear the long-term reward will never come, or at least be less certain of this outcome. This theory makes sense from an evolutionary perspective and has been supported in a study that found people with steeper discounting curves fared better in a simulated foraging task (Critchfield & Atteberry, 2003). In this study, participants were placed on teams

with a goal of collecting the highest amount of limited resources. The measure that best predicted individual success within each group was steeper delay discounting (measured by a separate task), suggesting the importance of taking the smaller, sooner reward in competitive situations with limited availability of resources that may mimic past environments.

A review by Angott (2010) includes working memory as a factor in delay discounting. It is generally understood that taxing working memory interferes with responding in a way that require more cognitive control. Hinson, Jameson and Whitney (2003) reported just this with regard to delay discounting: loading working memory in participants steepened their delay discounting curves. This may support a conclusion that the brain reverts to a more "automatic" strategy of processing rewards, and that this strategy is biased toward choosing the smaller more immediate rewards. This is in line with the previous discussion of the neurobiological dual processing systems discussed previously.

Withholding a reward for the future can induce unpleasant sensations. Loewenstein (1992) in analyzing the works of the economist Senior (1936), described how interest is "compensation to the holder of capital for enduring the pain of abstaining from consumption, which he viewed as among the most painful exertions of human will" (p. 8). Evidence supporting this theory includes the finding that when utilizing self-regulatory skills during a period of waiting for a reward, children are able to wait longer for the reward (Mischel, 1974). This distraction

technique theoretically lessened the “pain” of waiting and lends support to the theory that greater attention to the delay increases the likelihood people will not be able to stand the wait and choose a sooner reward.

This idea of perception of relativity of reward value and temporal interval has produced two primary psychological theories proposed to account for the discounting: perceived value-based accounts, and perceived time-based accounts. Loewenstein (1996) hypothesized that in the same manner that sensory proximity determines the strength of the appetitive response (e.g. greater saliva production and subjective reports on desire when French fries are placed directly in front of a hungry person, compared with those French fries across a football field), temporal proximity could affect the steepness of devaluation of rewards. This theory focuses on the perceived value of the rewards, whereas the perceived-time-based accounts focus on the perception of the delays as a significant contributing factor in delay discounting.

In the perceived-time-based accounts, it is hypothesized that we experience decreased sensitivity to longer time horizons; that is we do not perceive time objectively, but rather subjectively, where a week in the future is not perceived precisely equal to seven 24- hour periods that we have experienced this week (Ebert & Prelec, 2007). Kim and Zauberman (2009a) found in a correlational study that this decreased sensitivity to longer future time intervals, combined with a variable of individual time contraction (how long or short individuals perceive an interval of

time to be), predicts the steepness of the delay discounting curve. Specifically, they reported that greater contraction of time units (perceiving a time interval as longer) was associated with a steeper delay discounting curve, whereas diminishing sensitivity to future time was associated with a more shallow curve. Interestingly, an unpublished follow up to this study (Kim and Zauberman, 2009b) found no relationship between delay discounting and trait impulsivity, which has been historically associated with delay discounting. Despite this finding, many other studies to be discussed in the next section have provided evidence that the trait of impulsivity is linked with delay discounting in some way.

2.2 Impulsivity and Delay Discounting

The concept of impulsivity is a complex one, and there has understandably been difficulty converging on a unified definition. Moeller et al. (2001) describes impulsivity as "a predisposition toward rapid, unplanned reactions to internal or external stimuli with diminished regard to the negative consequences of these reactions to the impulsive individual or others." The Diagnostic and Statistical Manual of Mental Disorders, 4th edition (DSM-IV-TR) characterizes impulsivity as "a failure to resist an impulse, drive, or temptation to perform an act that is harmful to the person or others" (American Psychiatric Association, 1994). It would seem intuitive that someone with high levels of impulsivity may have difficulties optimizing their choices on a delay-discounting task that relies on being able to

withhold an immediate reward for a future reward. People with ADHD that exhibit higher impulsivity exhibit especially steep delay-discounting curves (Scheres, Lee, & Sumiya, 2008), though these curves flatten with administration of methylphenidate, a stimulant that affects the dopaminergic system (Sheils et al., 2009) (please see later discussion of ADHD).

Components of Impulsivity

The trait of impulsivity is thought to express itself across various domains, which can be grossly separated into dissociable cognitive and motor aspects. Motor impulsivity has been characterized by patterns of performance seen on tasks that require the participant to inhibit a prepotent motor response. For example, in a Go/NoGo stop signal task, participants are asked to respond to a stimuli with a motor response; however when some signal is provided before the stimuli, like an auditory signal, then participants are directed to withhold their response. The inability to withhold this response has been characterized as motor impulsivity and can be dissociated from measures of cognitive impulsivity mentioned above (Kaladjian et al., 2007). Logan, Schachar, and Tannock (1997) found that self-reported impulsivity correlated positively with inability to withhold a prepotent motor response on a stop signal task.

Robert at el. (2009) outlined many of the cognitive components of impulsivity as they are currently understood. The phenomena that paper classifies

under the umbrella of cognitive impulsivity include impatience, impulsive decision making (including reward decision making and speed of decision making), impaired reward learning, risk-taking, reflection impulsivity (a tendency to gather insufficient information before making a choice), and delay aversion for gratification. It is easy to see how many of these concepts could map on to delay discounting behavior. A study by Alessi and Petry (2003) did find a significant relationship between cognitive impulsivity and delay discounting in pathological gamblers. However, despite the intuition that self-reported impulsivity and delay discounting should be linked, the relationship is tentative, with few studies finding a strong relationship between the two (Kirby et al., 1999; Crean et al., 2000; Kirby and Petry, 2004; Reynolds, 2006). Correlations found in such studies tend to be low, often limited to subscales of self-reported impulsivity measures.

A scale commonly used to measure self-reported impulsivity is the Barratt Impulsiveness Scale-11 (BIS). Principle component analysis by Patton, Stanford, and Barratt (1995) of the BIS has found it loads on the following six primary order factors: attention, motor, self-control, cognitive complexity, perseverance, and cognitive instability. Further analysis by the same team has yielded three broad secondary factors onto which the BIS loads: attentional impulsiveness, motor impulsiveness, and nonplanning impulsiveness. A study examining the relationship between delay discounting and the BIS finds only the nonplanning factor of

impulsivity to be consistently associated with delay discounting in normative adults (de Wit et al., 2007).

A larger exploratory analysis of the hierarchicial structure of 11 self-reported impulsivity scales, including the BIS, found at least 7 principal components of impulsivity: Prepared/Careful, Impetuous, Divertible, Thrill and Risk Seeking, Happy-Go-Lucky, Impatiently Pleasure Seeking , and Reserved (Kirby and Finch, 2010). According to this study, delay discounting rates loaded on Impatiently Pleasure Seeking, and correlated with the impulsiveness and venturesomeness scales from Eysenck et al.'s personality scale developed in 1985, the I7. The authors of this study support a discounting model of impulsivity first proposed by Ainslie in 1975: impulsive choices arise because of the way the relative present values of delayed rewards change with the passage of time (Kirby and Finch, 2010). This leads to the important question of the role that time perception is playing in delay discounting.

2.3 Time Perception

Time perception is an adaptive function that facilitates the ability to predict and anticipate events, as well as organize and plan sequences of actions (Mangels, Ivry, & Shimizu, 1998). Several studies have noted the link between time perception, impulsivity, and an inability to delay gratification with increased rates of delay discounting (e.g. Reynolds and Schiffbauer, 2004; Takahashi , 2005; Barratt, 1983; van den Broek et al., 1992; Glicksohn, Leshem, & Aharoni, 2006). Supporting the hypothesis that the time perception may be playing a main role in delay discounting, it has been found that the same event taking place in past vs. future is valued differently (Caruso, Gilbert, & Wilson, 2008). Because perception of time is an important variable when studying delay discounting, it is worthwhile to explore precisely how it may be contributing to this type of decision making.

Lashley (1960) stressed the importance of temporal perception, writing that processing of complex stimuli relies on the ability to process order, interval, and duration of events. Temporal perception can be contrasted with more spatial processing and comparisons, such as those differentiating between angles of bars of light shone on the retina. Though virtually all complex processing combines aspects of both spatial and temporal dimensions, we will focus on time perception in this review.

How is time perception studied?

There are four chief methods in use to study time perception, as outlined by Wittmann and Paulus (2008): 1. A verbal estimation of time duration, in which a participant is asked to judge how long an elapsed time interval lasted; 2. a time duration task, in which participants are asked to judge when they believe a given duration of time has elapsed; 3. duration reproduction tasks, in which participants are exposed to a fixed interval of time and asked to reproduce it (i.e. reproducing a given tempo); and 4. duration comparison tasks, in which multiple intervals are presented and participants pick which was longest or shortest. Methods 1 and 2 require that participants explicitly translate their experience of passage of time into seconds and minutes, while methods 3 and 4 measure a judgment of relativity that does not require second/minute translation.

Cognitive Model of Time Perception

The prevalent cognitive model of time perception, referred to as the "pacemaker-counter process," assumes the existence of an internal clock system that generates and tracks temporal units (Zakay & Block, 1997). Wittman & Paulus (2008) outline this cognitive model established by Zakay & Block of time perception: a generator of units (or pulses of time) is referred to as the "pacemaker", and its tempo is mediated

by arousal, which in turn is moderated by various mood states. Mood state also moderates attention, and attention acts as a switch that turns on a mechanism to count the pulses of time generated by the pacemaker. This count is then transferred to short-term memory storage, and is used as a reference against a previously stored representation of what constitutes a "second" or "minute". A decision regarding this comparison is ultimately made, and the observed behavior output is the result of this decision (see Figure 2) (Pouthas & Perbal, 2004).

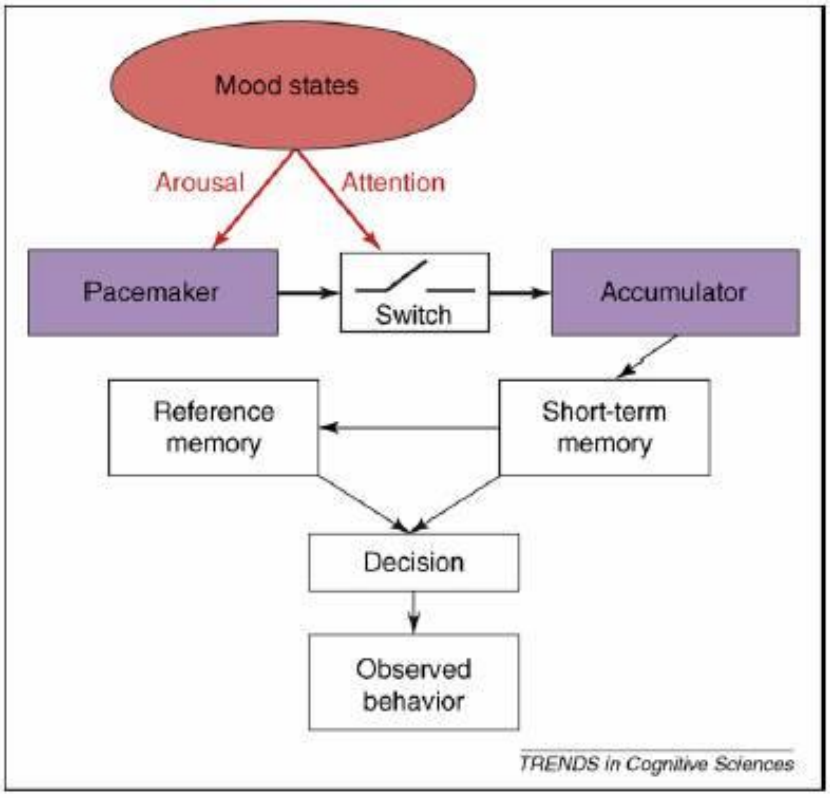


Figure 2. Cognitive model of time perception. Wittman & Paulus, 2008.

In this cognitive model, it is important to note that the pacemaker's rate of generating time pulses can be altered by arousal and mood states; it is not a constant internal time generator. The subjective experience of time duration is the amount of pulses counted by the accumulator as they feed into memory stores. This model implies that increased rates of pulses of time would lead to greater estimations of duration, as more pulses equals more time. Similarly, it predicts slowed rates of pulses generated by the pacemaker would induce underestimations of time duration. It has been found that increased arousal, in the form of anxiety, is associated with the perception of a slowing of time (i.e., overestimation of duration), presumably via a faster pacemaker (Wittman et al., 2006).

Attention can also affect time perception in this cognitive model: increased attention to time causes the accumulator (as opposed to the pacemaker as outlined above) to switch on, allowing for a greater number of "pulses," or subjective temporal units, to generate, which would induce overestimations of time. This phenomenon can be observed in normative individuals: when staring at a clock during a less engaging lecture, time seems to slow. The cognitive model explains this as increased attention causing increased pulses to accumulate, thus creating the subjective experience of increased duration of time. Similarly, in line with the saying "time flies when you're having fun", a lack of attention to the explicit passage of time will result in fewer time pulses being accumulated, and an underestimation of time duration (Burle & Casini, 2001). Smokers attempting to quit nicotine experience a

subjective slowing of time associated with increased perception of temporal duration, which is associated with greater attention to the passage of time (Sayette et al., 2005).

Another cognitive model of time perception is called the oscillator process model, which asserts that perception of time is based on a non-linear, dynamic system that attends to temporal intervals embedded in sequences of signals, such as music, speech, and movement (Jones & Boltz, 1989; Grondin, 2010). In this model, regularly repeating features of stimuli induce future-oriented attention, and create a "predictive state"- a tendency to predict the rhythmic pattern of stimuli. Temporal processing here relies on the synchronicity of attended internal rhythms (derived from predictions from external stimuli) with perceived external rhythms. An internal oscillator allows the internal attending rhythm to approach the external stimuli rhythms. Though this model can account for temporal processing, the pacemaker-counter process is currently the dominant view (Grondin, 2010).

Neurobiological Correlates of Time Perception

Many structures have been implicated in time perception, though in this review focus will be placed on the cerebellum, cerebral cortex, and basal ganglia, as they have received the most study in regard to explicit time judgment. Ivry, Keele, and

Diener (1988) found that lesions to the cerebellum increase the variance of interval reproductions. These patients also exhibited diminished ability to discriminate between brief time intervals, while their ability to discriminate intensity of sounds remained intact. Imaging studies have implicated both lateral and medial regions of the cerebellum in temporal processing across a range of durations, ranging from milliseconds (Lewis & Miall, 2003) up to approximately 24 seconds (Tracy et al., 2000).

Several regions of the cerebral cortex have been associated with time perception. Most of the literature has focused on the frontal and parietal cortices, as well as the supplementary motor area (SMA), as being the primary areas associated with time perception. A review by Grondin (2010) highlights several studies that implicate various structures: dorsolateral PFC has been associated with brief (<1 sec) time interval processing (Pouthas et al, 2005); while activation of the general right PFC has been associated with short as well as supra-second time processing (Koch et al., 2002). It is thought that the "accumulator" from the pacemaker-counter cognitive model of time perception is located in frontal cortex regions (Pfeuty, Ragot, & Pouthas, 2003). Binkofski & Block (1996) reported a case study of a previously healthy man who had a lesion of the left superior PFC: its effects included perceiving time much faster than previously. The man reported that his world appeared to be moving in fast-forwarded motion.

SMA activation has been observed when judging time intervals, as when participants are asked to explicitly count seconds (i.e. “one one-thousand, two one-thousand” or “one mississippi, two…”) (Hinton et al., 2004). Transcranial magnetic stimulation of the parietal lobe (specifically, right posterior parietal cortex) has also been associated with interval duration processing. TMS-induced disruption of this area resulted in decreased ability to discriminate time intervals, while the ability to discriminate tonal intervals remained intact (Alexander, Cowey, & Walsh, 2005).

Finally, the basal ganglia have been studied as a component of time perception: fMRI studies have found it is most likely involved with early temporal processing and the encoding of time intervals (Rao et al., 2001). Both the caudate and putamen are activated during short as well as longer time interval processing (Pouthas et al., 2005; Hinton & Meck, 2004). These brain regions are hypothesized to correlate with various aspects of the cognitive pacemaker-process model of temporal perception, as outlined by Grondin (2010): temporal perception depends on frontal-striatal circuits. The command to “start timing” travels from cortical areas to the striatum via topographically-linked fibers. Single-unit studies in monkeys have shown that cells in the striatum previously firing at non-united intervals then synchronize and create a pattern of neural activity, which is hypothesized to correspond to the cognitive pacemaker (Beiser and Houk, 1998). The striatum encodes these bursts of activity, and receives a message from the substantia nigra to stop firing: when dopamine antagonists (specifically for the D2 receptor) are

administered, interval duration estimations decrease significantly (Meck, 1986). This phenomenon is mirrored in Parkinson's patients whose substantia nigra is dysfunctional (Malpani et al., 1998). It is hypothesizd that the striatal activity is recorded via these dopamine bursts as the interval length (Rammsayer, 2008).

Dopamine has been implicated in several studies as playing a significant role in time perception; or at least that its manipulation affects time perception. Administration of a D2 receptor antagonist has been shown to decrease pacemaker speed in both animals and humans (Rammsayer, 1993). In contrast, administration of D2 receptor agonists appears to increase the temporal pacemaker in animals (Cheng, MacDonald, & Meck, 2006). When patients with depleted dopamine levels with Parkinson's Disease are administered dopamine replacement therapy (DRT), the normally decreased pacemaker is restored to "normal" rates (Pastor et al., 1992). This is compared with over-reproduction of a second when DRT is suspended (Malpani et al., 1998). This dopamine theory, which places significant emphasis on optimal dopamine levels for accurate time perception, integrates well with findings on time perception issues in ADHD. In addition, the previously mentioned structural studies of temporal perception correspond with areas implicated in ADHD: the frontal cortex, basal ganglia, and cerebellum (Giedd et al, 2001).

2.4 ADHD and Time Perception

A primary time-processing deficit has been suggested as a neuropsychological endophentype of ADHD. Numerous studies have found an impaired sense of timing ranging from the scale of milliseconds to multiple seconds in ADHD populations (Barkley, et al., 2001; McInerney & Kerns, 2003; Smith et al., 2002; Valko at al., 2010). Marx et al. (2010) found that children, adolescents, and young adults with ADHD exhibited difficulties with both time discrimination and time reproduction when compared with age-matched normative controls. Valko et al. (2010) found these deficits continue to exert their effects well into adulthood.

Although in several studies a bias toward temporal overestimation in those with ADHD is observed, the most consistent finding is that people with ADHD exhibit more variability in their response behaviors: the error variability is more erratic than the normative population (Castellanos & Tannock, 2002). These findings have been explained by various hypotheses, many of which implicate to a degree dopamine dysfunction (Levy & Swanson, 2001; Lowe et al., 2004; Sagvolden et al., 2005). One explanation of the finding of impaired timing sense is that dysregulated dopamine contributes to working memory deficits, impaired response inhibition, and poor executive functioning (Barkley, 1997). Thus second-to-second experience and responses to the environment appear to be impaired. Interestingly, administration of methylphenidate, a psychostimulant affecting the dopamine

system, has been found to decrease response variability and resulted in more precise performance on temporal processing tasks, attributed to an enhancement in working memory (Baldwin et al., 2004).

There are also neurobiological structural differences that support an intrinsic time perception deficit in those with ADHD: reductions in volume of prefrontal (Mostofsky, et al., 2002), basal ganglia (Semrud-Clikeman et al, 2000) and cerebellar (Castellanos et al., 2002) regions, all associated with time perception and processing, have been observed in those with ADHD when compared with normative controls.

Gilden and Marusich (2009) found evidence for a contracted sense of timing in ADHD manifesting as a loss of rhythm perception or feeling at slowed tempos. This is contrasted with normative controls who were able to maintain and "feel" the rhythm at significantly slower tempos than the ADHD group. This lends evidence to the theory that the implicit working memory system of those with ADHD may be compromised and be affecting sense of time. This contraction of time may underlie the finding that durations are often overestimated by people with ADHD.

Sonuga-Barke et al. (2010) have proposed a triple pathway model to explain some of the cognitive and motivational deficits observed in ADHD. This model emphasizes a primary temporal processing deficit, in addition to poor inhibitory control and increased delay aversion. These three components were shown to be

dissociable in an ADHD population, and separated participants from normative controls.

Other Factors Affecting Time Perception

In addition to intrinsic attentional difficulties, several other factors have been found to affect time perception. As predicted by the previously discussed prevalent cognitive model of time perception, explicit attention to time is associated with temporal over-estimation (Twenge et al., 2003). Several physiological states are associated with differences in time perception: an increase in body temperature is linked with temporal overestimation (Hancock, 1993), as is an increase in adrenaline brought about during stressful events (Eagleman at al., 2005). Emotional factors appear to play a role as well: happiness induced by happy music led to underestimation of interval duration, while sadness induced by sad music was associated with temporal overestimation (Bisson, Tobin, & Grondin, 2009). However, markedly less emphasis has been placed on the influence of more external factors and their effects on time perception.

External Tempo and Time perception

Very few studies have examined the effects of external tempo on time perception. Zakay, Nitzan, & Glicksohn (1983) found that judgment of time intervals depended

on the tempo set by a buzzer. Specifically, there was a direct relationship between tempo and time interval duration estimation: overestimations of time were associated with fast tempo, while underestimations associated with slow tempo. This would be in line the cognitive model of temporal perception: faster tempo would be interpreted as more time units being ticked off (the internal pacemaker being influenced by the external stimulus with greater arousal associated with faster tempo), with greater overall accumulation, and thus overestimation of time, with the opposite holding true for slow tempo. Feedback, or contextual information, during a temporal reproduction task also increases later accuracy: when participants are required to tap along in time with an accurate clock, they are more accurate at later estimating time (Dutke, 2005).

Wearden, Philpott, and Win (1999) found that short trains of clicks at different tempos were able to induce overestimation of duration of an auditory stimulus that followed the clicks. They also included a condition with clicks and no clicks preceding the tone stimuli. The tone stimuli were in reality the same duration for all conditions. When a tone was preceded by clicks at 5 Hz, the tone was judged as lasting longer than the tone preceded by no clicks. A tone preceded by clicks at 25 Hz was judged to last longer than a tone preceded by clicks at 5 Hz. They were unable to create a condition in which the duration of the tone was perceived as shorter than it was. This finding was replicated in 1996 by Penton-Voak et al., with the proposed explanatory mechanism being that the clicks were speeding up an

internal pacemaker. Possible biological substrates of such a pacemaker were not explored in these papers.

Several studies have examined the impact of tempo on time estimation within the marketing field, typically studying how ambient tempo affects estimations of time spent shopping). Polkosky & Lewis (2002) found that faster auditory tick rates while on hold on a phone were associated with temporal overestimation (as well as greater anxiety, stress, and impatience). Slower ticking was associated with temporal underestimation, but also induced greater stress than a silent condition.

Finally, at least one electrophysiology study examined the effect that external tempo has on internal states. In this EEG study, it was hypothesized that external visual information may directly affect some internal timekeeping mechanism (Johannes et al., 1997). The study found that when flashes of light with a set tempo were shown to participants, the alteration of brainwave patterns was associated with more accurate predictions of when the light will flash next.

2.5 Working Memory and Delay Discounting

Working memory is the part of the cognitive system that is used to hold a limited amount of information in the focus of attention (Hinson, Jameson, & Whitney, 2003). It provides temporary storage and processing of information for use in guiding behavior (Baddeley, 2007). Deficits in working memory are linked with poorer

learning, comprehension, and academic achievement (De Jong, 1998; Gathercole, Pickering, Knight, & Stegmann, 2004). Working memory is necessary for performing complex tasks such as planning, problem solving, and decision-making.

Several studies have found that increasing demand on working memory is correlated with less optimal performance on versions of the Iowa Gambling Task, a probability-based decision making task (Worthy, Otto, & Maddox, 2012; Dretsch & Tipples, 2007; Bechera & Martin, 2004). However, there are limited studies that have examined more directly the relationship between working memory and time-based decision-making tasks like delay discounting. Hinson, Jameson, & Whitney (2003) found that by placing a load on working memory capacity during a computerized delay discounting task, they could steepen (increase) the *k* value of participants' delay discounting curves. Participants who had greater demand on their working memory made more impulsive choices and favored suboptimal temporally proximal rewards over delayed optimal rewards. However, a later review of this study provided an alternative explanation of these findings, stating that increased working memory load appeared to merely increase the likelihood of random responding on the delay discounting task, rather than eliciting a clear preference for the immediate choice (Franko-Watkins, Pashler, & Rickard, 2006).

While the 2003 study did examine increasing working memory load and its effects on *k*, studies that examine intrinsic working memory capacity and its relationship with delay discounting are largely absent from the literature. An

exception is a 2008 imaging study by Shamosh et al. that found intrinsic working memory capacity predicted delay discounting in normative controls, though only via mediation by Full Scale IQ. In addition, a study by Bickel et al. (2011) found that working memory training decreased *k* discounting values in a sample of people with stimulant addictions.

Though these few studies have examined the relationship between working memory and delay discounting in primarily normative populations, a literature search finds no studies that examine working memory capacity in an ADHD population and its effects on delay discounting. Impaired decision-making performance on the Iowa Gambling Task has been observed in children with ADHD, but this task does not explicitly involve judgments involving the passage of time (Garon, Moore, & Waschbusch, 2006). Therefore, a measure of working memory capacity in an ADHD clinical population will provide information about the relationship between working memory and delay discounting.

2.6 Processing Speed and Delay Discounting

Processing speed refers to the speed of cognitive processes involved in selecting, preparing, and executing a response. Processing speed is a significant component of overall IQ, is correlated with working memory, and has been found to account for a high degree of age-related memory decline in non-demented older adults (Fry & Hale, 1996). Salthouse (1996) has proposed that slower processing

speed may leave more time for information stored in working memory to decay, which would lead to lower effective working memory capacity.

Despite the close linkages between processing speed and both working memory and overall IQ, its independent contribution to delay discounting is understudied. A 2008 unpublished master's dissertation found no relationship between processing speed and delay discounting in a sample of normative participants (Rambo, 2008). A 2006 study by Hoffman et al. found no significant relationship between trails A or the Stroop color/word (non-interference condition) tasks with delay discounting rates in a group of methamphetamine-addicted individuals. No studies were found that examined the relationship between processing speed and delay discounting in a clinical population with known impairment with processing speed such as an ADHD group.

2.7 Working Memory, Processing Speed, and ADHD

Deficits of both working memory and processing speed in people with the diagnosis of ADHD are widely cited. A meta-analysis of 26 studies found that working memory deficits were associated with the diagnosis of ADHD, independent of comorbidity with other language learning disorders and general intellectual ability (Martinussen et al., 2005). Processing speed deficits have been observed in ADHD populations in a large number of studies (see Jacobson et al., 2011 for a review; Shanahan et al., 2006).

It has been hypothesized that working memory deficits may play a causal role in many of the cognitive / behavioral deficits seen in ADHD, such as disorganization, inattentiveness, poor social skills, and hyperactivity (Kofler, Rapport, Bolden, & Altro, 2008). In addition, underlying working memory deficits may also be responsible for delay aversion and impulsivity (Rapport et al, 2001).

A proposed inverse relationship between processing speed and perceived time passage has been suggested in a theory paper by Goddard (2000), who hypothesized that this could relate to ADHD. Specifically, he wrote that ADHD could be caused by a distorted sense of time in which time passes so quickly that concentration becomes difficult.

Chapter 3: Summary and Hypotheses

To summarize, delay discounting is a behavior manifesting a tendency to devalue future rewards with respect to present rewards. This behavior is associated with many clinical populations and has been shown to be associated with poor outcomes. To better understand what underlies delay discounting, we may examine the primary variable that is changing within the paradigm, the variable of time. Several clinical populations (notably, ADHD), have been shown to have deficits, or at least differences, in time perception. The purpose of this study is to determine if an altered sense of time in the seconds-range is associated with decision tasks involving longer delays.

Additionally, the relationship between delay discounting and working memory and processing speed is understudied, especially in an ADHD population. Though several studies have examined the effects that manipulating working memory via loading or training has on delay discounting in normative and substance abuse groups, no known studies have examined the role that intrinsic working memory and processing speed capacity may play in delay discounting. Significant working memory and processing speed deficits are observed in those with ADHD compared with normative controls, as is increased delay discounting. This study will examine to what degree working memory and processing speed capacity may underlie delay-discounting behavior in an ADHD population.

Optimal decision-making requires the ability to maintain, access, and manipulate stored information and compare it to another piece of information. If working memory capacity is decreased, then presumably fewer pieces of information can be accurately maintained, manipulated, and compared with other pieces of information. With the many comparisons and values to consider in delay discounting (both money values, both time values), it may be possible that lower working memory capacity may interfere with making the less impulsive choice.

In addition, processing speed may be related to the construct of the "internal pacemaker," with faster processing speed associated with a faster pacemaker / sense of time. The prevalent theory of cognitive time-keeping suggests that a faster internal temporal pacemaker is associated with greater estimations of time durations (due to greater accumulation of temporal units). However, those with ADHD tend to have greater variability in estimations of time duration but consistently *slower* processing speed. Therefore further exploration into the interaction between processing speed, working memory, sense of time, and decision-making is warranted.

Hence, the current study has the following specific aims:

(1) To establish if feedback from a device regarding the length of a second can influence temporal duration estimations;

(2) To determine if this manipulation of local temporal perception affects rates of delay discounting;

(3) To explore how this manipulation of local temporal perception affects delay discounting in an ADHD population;

(4) To explore the role self-reported impulsivity may be playing in the relationship between manipulated temporal perception and delay discounting.

(5) To determine if intrinsic working memory and processing speed capacity have a significant influence on delay discounting;

(6) To explore how working memory capacity and processing speed affects timing training to a metronome.

Hypotheses

It is hypothesized that

(1) Feedback from a false metronome will affect brief (~20 sec) time interval estimates in the following ways: active feedback training to 50 beats per minute (bpm), but labeled as 60 bpm / 1 beat per second, will induce under-estimations of brief time intervals. Active feedback training to 70 bpm (labeled also as 60 bpm / 1 beat per second) will induce over-estimations of time intervals.

(2) Those who have been trained with the slow tempo (50 bpm) will show decreased rates of delay discounting in a delay discounting task with respect to those trained with the fast tempo (70 bpm).

(3) The clinical ADHD group will exhibit delay discounting patterns similar to the non-ADHD group in response to the metronome training, but the effect will be smaller due to inherent greater variability of temporal perception in the ADHD group.

(4) Higher levels of trait impulsivity in all groups will be associated with higher rates of delay discounting, with high impulsivity and exposure to fast metronome correlated with steepest delay discounting.

(5) Working memory capacity will have a significant influence on delay discounting; specifically, lower working memory capacity will be associated with increased delay discounting rates. Processing speed capacity will have a significant influence on delay discounting; specifically, slower processing speed will be associated with increased delay discounting rates.

(6) Working memory capacity will influence time estimation. Specifically, lower working memory capacity will be associated with

a. less accurate time estimations of both short-term and long-term time intervals

b. more training trials needed to reach criterion on metronome task

Processing speed capacity will influence time estimation. Specifically, slower processing speed will be associated with

a. less accurate time estimations of both short-term and long-term time intervals

b. more training trials needed to reach criterion on metronome task

All statistical tests are performed at the .05 level of significance.

Chapter 4: Methods

4.1 General Design

This study examined the effects of exposure and training to a slow metronome ("S") or fast metronome ("F") on delay discounting in an ADHD and non-ADHD population. Additionally, it examined how impulsivity, working memory, and processing speed may moderate these results. Metronome condition (slow or fast) and diagnostic group (no ADHD, ADHD on medication, ADHD off medication) were main independent variables, *k* (steepness of delay discounting) was the main dependent variable, and self-reported impulsivity (obtained from the BIS-11), working memory capacity, and processing speed were other predictor variables. The specific statistical test used for each aim of the study is described below in the results.

4.2 Setting

The study took place in the Seay Building at the University of Texas at Austin, within the Clinical Neuropsychology Lab.

4.3 Tasks

Demographic / ADHD questionnaire (see Appendix A)

Information on gender and age was collected. Information on ADHD diagnosis (how many years with diagnosis, subtype) and medication (medication name, dosage, whether or not the participant was currently on medication) was collected as well.

Metronome Task

Participants were randomized to either the slow (S) or fast (F) metronome group. Participants were advised that since this is a study about timing, they would have to remove any watch and put away their cell phones. They were then provided with sham educational material (see Appendix B), which emphasized the importance of accurate time-perception, with such statements as "studies have shown that accurate prediction of time intervals predict later success, wealth, and self-reported happiness" and "we are attempting to train people to be more accurate time keepers so that more people can experience these measures of success". The statements were provided to attempt to induce greater motivation and adherence to the manipulation.

After reading through the sham education materials, participants entered a room with a computer and metronome. The researcher was equipped with a smartphone onto which a metronome program application ("Mobile Metronome") had been loaded. Participants were told that the metronome was set to 60 beats per minute, one beat per second. The researcher explained that the goal was to learn

how to more accurately estimate time durations by getting an improved sense of the accurate length of a second. The researcher then "verified" the rate of the metronome with the smartphone by playing synchronous beats for several seconds (however, the smartphone was set to match the rate of the metronome, rather than 1 beat per second). The participant was asked to listen to the metronome and encouraged to tap along with the beat "to really get a feel for the length of a second." The metronome then was started and continued running for approximately 20 seconds. Participants were not told how much time had elapsed.

Following this exposure, the metronome was turned off and the participant was asked to indicate when they believed 20 seconds have elapsed. Timing commenced with a stopwatch so the researcher could record how much time had passed. Participants' answers were recorded. Participants were required to show a consistent under or overestimation of the time interval (depending on the tempo target), with consistency defined as at least 3 trials below or above the target time. Specifically, exposure to the metronome set to 70 bpm had to yield three estimations of a 20 second interval equal to or under 18 seconds to be considered successful training. Exposure to the slower metronome (50 bpm) had to yield three estimations equal to or over 22 seconds to be successful. It was planned to provide up to 10 learning trials, though 7 was the maximum number needed by any single participant. The minimum number of trials administered was 3. The number of

training trials required to achieve 3 trials within the specified range was recorded as an index of "trainability" to the manipulation.

Barratt Impulsiveness Scales-11 (BIS-11) (see Appendix C)

The BIS-11, a self-report questionnaire, has been validated in impulsive and normative populations. It consists of 30 items that have been divided into three subscales: attentional (inattention- 5 items and cognitive instability- 3 items), motor (motor impulsiveness- 7 items and lack of perseverance- 4 items), and nonplanning (lack of self-control- 6 items and intolerance of cognitive complexity- 5 items). Total points for each subscale and total score on the entire BIS-11 were used in the present study. While some previous studies (e.g. Swann et al, 2002) have shown that high impulsivity is correlated with steeper delay discounting, this finding has not been consistent and requires further exploration.

Adult Self-Report Scale Symptoms Checklist (ASRS); Adler, et al., 2005; (Appendix D)

The ASRS, a self-report questionnaire designed to examine ADHD, has been validated in ADHD and normative populations. It consists of 18 questions separated into inattentive and hyperactive/impulsive categories. Of the 18 questions, there are 9 in the Inattentive section and 9 in the Hyperactive/Impulsive section, corresponding to the DSM-IV criteria for ADHD. Each question is rated on a 5-point likert scale, yielding values between 0 (corresponding to "never") and 4

(corresponding to “most of the time”). The total sums of points for both the Inattentive and Hyperactive/Impulsive symptom sections were entered into the model separately to examine the effects of ADHD symptomatology on the relevant study aims.

Wechsler Adult Intelligence Scale-IV (WAIS-IV): Matrix Reasoning

In this task, participants examine a visual design or set of designs and are presented with 5 options to pick from to best complete the design. This task incorporates visual processing and abstract, spatial reasoning. Performance on the Matrix Reasoning task served as a performance-based IQ measurement to ensure that groups did not differ in IQ. Raw scores (ranging from 0-26 for number of correct items achieved before the discontinuation rule of 3 incorrect in a row) were used as performance variables rather than age-corrected scaled score to allow greater variability of scores within the very narrow age range of participants tested. Participants were also required to provide an estimation of how much time they believe they spent on the Matrix Reasoning task. They were not warned beforehand that they would be required to make this estimation. This estimation served as another measure of time processing on a somewhat larger scale than the 20-second estimations, allowing for an examination of the generalizability and duration of any effects the manipulation may have had.

Delay Discounting Computerized Task

This served as the main experimental task, with steepness of delay discounting (*k*) as the main dependent variable for the study. A description of the delay discounting task is outlined as follows (with assistance from Schoenberg [2011]). This task was run on MatLab on a PC and used a computerized adjusting-amount procedure to measure discounting of delayed monetary reinforcers. The program presented participants with an initial amount of either $5 or $10. There were three original possible delays (30 days, 60 days and 90 days), counterbalanced throughout the sample. The dollar amount of the delayed option ranged from $6 to $120 and was determined adaptively with a staircasing procedure (Du, Green, & Myerson, 2002). Based on previous literature, it was assumed that each participant's pattern of discounting the value of the delayed option will follow a hyperbolic curve (Kable & Glimcher, 2007; Monterosso et al., 2007). The parameter describing the steepness of the curve (*k*) has an average value of approximately 0.013 based on previous results from studies in normative adults (Kable & Glimcher, 2007; Kirby, Petry, & Bickel, 1999; Monterosso et al., 2007). Assuming a hyperbolic discounting function, the equation to determine the subjective value of a delayed option is SV = V=(1 + kD) where SV = the subjective value of the payment after accounting for its discounted value, V = the numerical value of the payment, *k* = the individual's discounting parameter, and D = the delay in days of the payment.

The indifference point of each option, where the subjective value of the

delayed amount is equal to the actual value of the immediate amount was calculated for each participant. This resulted in an option where a person with the same discounting parameter will feel that the two options were equivalent. This allowed the calculation of the actual value of the delayed amount given the delay and the immediate amount: V = SV / (1 + kD) where SV is equal to the immediate amount on any given trial.

There were 48 adaptive trials: 24 with each immediate value ($5 and $10, and 8 occurrences of each delay for each starting value). The immediate and delayed amounts were randomly presented in either the left or right sides of the computer screen. The task began by assigning a *k*-value of 0.013 (the average in the normative adult population) to each of two staircases, one assigned to all immediate $5 options and a second assigned to all immediate $10 options. A combination of the *k*-value, the delay, and the immediate amount was used to determine the delayed amount presented to the participant. The only constraint to this approach was that the maximum delayed amount was capped at $120. After each trial, the *k*-value was updated based on the QUEST toolbox in MATLAB (Watson & Pelli, 1983).

The QUEST parameters were as follows: starting estimate (0.013), standard deviation (.02), probability of choosing delayed (0.5), Weibull function parameters (beta =5, delta = 0.01, gamma = 0.01), step size (0.001), and range of responses (1). If a participant chose the immediate amount, the indifference *k*-value on that trial was smaller than the person's actual *k*-value and it was increased on the next trial. If

a participant chose the delayed amount, the indifference *k*-value was decreased on the next trial. This procedure was used so that the staircases converged at the person's indifference *k*-value by the end of the run. Order of immediate amount and delay were random.

After 3000 ms if no response was made, a prompt appeared underneath the option to remind participants to respond. After the choice was made, a fixation crosshair was displayed for 1000 ms before the next trial began. The *k*-values collected provided a quantitative index of the steepness of the discount curve: higher *k*-values reflect greater, steeper discounting by delay.

Finally, upon completion of this computerized task, an estimation of time spent doing this task was collected and used as another measure of time processing to examine the generalizability and duration of the metronome manipulation task.

Wechsler Adult Intelligence Scale-IV (WAIS-IV): Digit Span

Digit span is a measure of attention, concentration, and working memory capacity. Participants are required to repeat a series of aurally presented numbers of increasing length in 1) the order of presentation, 2) in reverse order and 3) in ordinal sequence. Test-retest reliability is .83 (Lichtenberger & Kaufman, 2009). For the current study, the combined raw score on digits forward, digits backward, and digits sequenced will be the main variable analyzed in this task. In addition, the impact of the raw score of reverse digit alone will also be analyzed.

N-back Computerized Task for Matlab (adapted from Multidimensional-N-back, Nick Penaranda, George Mason University)

The N-back task is a continuous performance task designed to measure working memory ability. A sequence of letters appear on a computer screen one letter at a time, and participants are required to compare the current letter with the letter they saw 3 screen previous. They are asked to indicate whether it was the same letter or a different letter by button response. For the current study, the number correct of 100 trials will be the main variable analyzed in this task.

Wechsler Adult Intelligence Scale-IV (WAIS-IV): Symbol Search

Symbol Search is a measure of processing speed that requires participants to decide if either of two visual designs is represented in a span of five designs. Participants have 120 seconds to complete as many of the 60 items as possible. Test-retest reliability for this measure is 0.81, and is correlated .65 with digit-symbol coding, another measure of processing speed (Lichtenberger & Kaufman, 2009). For the current study, raw score of correct items completed in 120 seconds will be the main variable examined.

Color naming task (adapted from D-KEFS Color/Word Interference Test)

Color naming is a measure of processing speed that requires participants to verbalize the names of 48 rectangular color blocks as quickly as possible without the confounding effect of reading ability. For the current study, time in seconds required to name the colors was the main variable examined.

Debriefing and Manipulation check (appendix E)

This form examined to what degree the participants believed the metronome was accurate on a scale of 1 to 5, and then provided debriefing information.

4.4 Procedure

All participants filled out an informed consent form. Upon completion, they were asked if they had any questions. Any questions were answered, and participants were then provided with the sham educational material and completed the metronome task manipulation as described above.

Immediately following successful manipulation, participants were provided with instructions and then administered the computerized delay discounting task. Upon completion of the delay discounting task, participants were asked to estimate the duration of time they spent doing the computerized task. Next, they were administered the Matrix Reasoning subtest from the WAIS-IV. Once they reached discontinuation criteria for this subtest (three incorrect answers in a row), they again were asked for an estimation of how long they spent on that task. Actual time

elapsed for both the delay discounting task and Matrix Reasoning was recorded as well to obtain an accuracy score by subtracting estimated duration from actual duration.

The 81 participants from the 2nd wave of the study were then administered a color-naming task adapted from the Delis-Kaplan Executive Functioning System, the Digit Span subtest from the WAIS-IV, the Symbol Search subtest from the WAIS-IV, and a computerized N-back task.

Following completion of the cognitive tasks, all participants filled out the questionnaires in the following order: 1. Demographics, 2. BIS-11, 3. ASRS. All participants were then asked to rate on a scale of 1 – 5 to what degree they believed the metronome was accurate (i.e., actually beating at 60 bpm) to obtain a measure of how much they believed the manipulation represented accurate timing. Finally, participants were debriefed by the researcher that the metronome was inaccurate. Each participant was provided with a debriefing form explaining the experiment, revealing the inaccuracy of the metronome, and providing educational information about the nature of the study with contact numbers for any additional questions.

4.5 Participants and Recruitment

Recruitment. Participant recruitment was initiated upon The University of Texas at Austin IRB approval of the study and was conducted through three means. First, recruitment occurred through the PSY 301 subject pool at The University of Texas at

Austin, which allows students enrolled in introductory psychology classes to obtain course credit through participation in research as subjects. Subjects were recruited for this study through a static posting in the online subject pool management system known as OPERA. Secondly, posters approved by the IRB to target students with ADHD were placed at the Services for Students with Disabilities office in the Student Services Building at UT. Thirdly, in coordination with Austin Neuropsychology, PLLC, patients (age 18+) with a clinical diagnosis of ADHD and who had previously provided consent to be contacted as potential study participants were provided information regarding this study and an invitation to participate.

Inclusion / Exclusion Criteria. Participants with a self-reported history of head injury with resultant loss of consciousness; epilepsy; comorbid psychiatric diagnosis; and current intoxication were excluded from the study. Hearing and vision were adequate for testing purposes for all participants, verified by their ability to correctly follow written directions on the forms and computer screen and appropriately respond to the researcher's auditory questions. Participants were 18 years or older (range: 18 – 27; M = 19.22; SD = 2.12).

For the ADHD group, either self-report of registration with the Office of Students with Disabilities for ADHD or diagnosis from Austin Neuropsychology, PLLC, was required. For inclusion into the study, participants with a diagnosis of ADHD were also required to bring in a bottle of their current stimulant medication

with their name on the label. An ADHD symptoms checklist (ASRS) was completed by both the normative controls and the ADHD group. Participants were asked to abstain from stimulant medication for 24 hours prior to the testing. Despite this request, 17 of 38 ADHD participants did take their medication the day they were tested. Thus, current medication state (e.g., on or off stimulant medication) was included as another variable in statistical analyses as outlined in the results.

Chapter 5: Results

5.1 Summary of Collected Data

One hundred thirty-nine individuals participated in the study. Seven participants were excluded due to spoiled data collection (equipment malfunction). Of the remaining 132 participants, 38 had a clinical diagnosis of ADHD and 94 had no history of ADHD. All participants were included in the analyses that address study aims 1-4. Analyses for study aims 5 and 6 were completed using the entire sample of 38 participants with a diagnosis of ADHD and 37 non-ADHD participants. Group characteristics are presented below for each data set.

5.2 Group Characteristics

Demographics: *Study Aims 1-4*.

TOTAL PARTICIPANTS (STUDY AIMS 1-4) N=132				
DEMOGRAPHIC FACTOR	NON-ADHD (N=94)	ADHD- ON MEDICATION (N=17)	ADHD- OFF MEDICATION (N=21)	STATISTIC
Age mean years (SD)	19.41 (1.54)	19.35 (1.41)	19.14 (1.32)	$F(2,131)=0.286$; $p=.752$
Gender % male	33.0	52.9	52.4	$X^2(2)=3.918$; $p=.141$
Handedness % right handed	88.3	82.4	100	$X^2(2)=0.414$; $p=.520$

Table 1: Group characteristics for study aims 1-4.

A one-way ANOVA determined age did not significantly differ across the diagnostic groups. Chi-squared testing found gender composition ratios did not differ across

diagnostic groups. There were significantly more right-handed participants than left-handed participants in both ADHD groups (binomial test p=.000), as well as the non-ADHD group (binomial test p=.000), but no differences in rates of left handedness across these groups. All 132 participants, with one exception from the ADHD on medication group, were current undergraduate college students at the University of Texas at Austin.

Demographics: *Study Aims 5 & 6*.

TOTAL PARTICIPANTS (STUDY AIMS 5&6) N=75				
DEMOGRAPHIC FACTOR	NON-ADHD (N=37)	ADHD- ON MEDICATION (N=17)	ADHD- OFF MEDICATION (N=21)	STATISTIC
Age mean years (SD)	19.30 (1.49)	19.35 (1.41)	19.14 (1.32)	$F(2,74)=0.119$; p=.888
Gender % male	35.1	52.9	52.4	$X^2(2)=2.330$; p=.312
Handedness % right handed	91.9	82.4	100	$X^2(2)=3.976$; p=.137

Table 2: Group characteristics for study aims 5 & 6.

A one-way ANOVA determined age did not significantly differ across the diagnostic groups. Chi-squared testing found gender composition ratios did not differ across diagnostic groups. There were significantly more right-handed participants than left-handed participants in both ADHD groups (binomial test p=.000), as well as the non-ADHD group (binomial test p=.000), but no differences in rates of left handedness across these groups.

Adult ADHD Self-Report Scale (ASRS).

ASRS FACTOR	NON-ADHD: STUDY AIMS 1-4 (N=94) **MEAN (SD)**	NON-ADHD: STUDY AIMS 5 & 6 (N=37) **MEAN (SD)**	ADHD- ON MEDICATION (N=17) **MEAN (SD)**	ADHD- OFF MEDICATION (N=21) **MEAN (SD)**
Inattentiveness (possible range: 0-36)	14.24 (4.18)	15.16 (4.05)	22.12 (5.78)	22.43 (5.17)
Hyperactivity/ Impulsivity (possible range: 0-36)	10.95 (4.83)	10.00 (4.06)	19.35 (6.85)	18.24 (6.02)
Total Score (possible range: 0-72)	25.09 (7.74)	24.89 (6.39)	41.47 (11.35)	40.67 (10.11)

Table 3: ASRS scores for diagnostic groups.

A one-way ANOVA was used to determine if ASRS scores for inattentiveness, hyperactivity/impulsivity, and total score differed by diagnostic group (i.e., no ADHD (N=94), ADHD on medication (N=17), ADHD off medication (N=21)) for the participants used in study aims 1-4. Please see table above for descriptive data. Results of the ANOVA revealed significant differences between groups for inattentiveness score: $F(2,129)=42.010$, $p=.000$; hyperactivity/impulsivity: $F(2,129)=29.254$, $p=.000$; and total score: $F(2,129)=45.889$, $p=.000$. Post-hoc testing using the Bonferroni correction for multiple comparisons found that participants without ADHD endorsed significantly lower levels of inattentiveness, hyperactivity/impulsivity, and total scores than both the ADHD on medication and ADHD off medication groups, $p=.000$. There were no significant differences in ASRS scores within the ADHD group depending on medication status.

The same pattern of results was observed when comparing the subset of controls (N=37) used in study aims 5 and 6 with the ADHD participants: a one-way ANOVA found there were significant differences between groups for inattentiveness score: $F(2,72)=20.673$, $p=.000$; hyperactivity/impulsivity: $F(2,72)=25.142$, $p=.000$; and total score: $F(2,72)=31.566$, $p=.000$. Post-hoc testing using the Bonferroni correction for multiple comparisons found that the participants without ADHD endorsed significantly lower levels of inattentiveness, hyperactivity/impulsivity, and total scores than both the ADHD on medication and ADHD off medication groups, $p=.000$.

The World Health Organization categorizes scores for both the Inattentiveness subscale and the Hyperactivity/Impulsivity subscale on the ASRS as follows: 0-16 = Unlikely to have ADHD; 17-23 = Likely to have ADHD; 24+ = Highly likely to have ADHD. The results above show that the mean scores on both Inattentiveness and Hyperactivity fall in the "Unlikely to have ADHD" category for the non-ADHD group; while both of these scores for both ADHD groups fall into the "Likely to have ADHD" category. It is important to note that other criteria outlined in the DSM-IV are required for a diagnosis of ADHD. Therefore, while scores on the ASRS reflect ADHD symptomatology, these scores in isolation are insufficient to rule in or to rule out a diagnosis of ADHD.

Number of participants meeting classification cutoff scores on ASRS	NON-ADHD: STUDY AIMS 1-4 (N=94)	NON-ADHD: STUDY AIMS 5 & 6 (N=37)	ADHD- ON MEDICATION (N=17)	ADHD- OFF MEDICATION (N=21)
Predominantly Inattentive Classification	18	11	3	6
Predominantly Hyperactive/Impulsive Classification	4	0	0	0
Combined Type Classification	6	1	13	13
Total meeting at least one classification; (% of total sample)	28; (29.8)	12; (32.4)	16; (94.1)	19; (90.5)

Table 4: Classifications by diagnostic group based on ASRS scores.

See table above for information on participants for all groups who meet ADHD classification for the three subtypes of ADHD based on ASRS scores.

Twenty-eight of 94 of the controls for study aims 1-4 self-reported ASRS scores above the threshold for ADHD classification, as did 12 of the subset of 37 controls used for study aims 5 and 6. Thus, analyses were run both including these participants and excluding them when ADHD diagnosis was a factor examined. Additionally, scores from the ASRS were used as continuous variables when indicated in the following analyses to further explore any contributing role of these symptoms, regardless of clinical diagnosis.

Barratt Impulsiveness Scale- 11 (BIS-11).

BIS-11 FACTOR	NON-ADHD: STUDY AIMS 1-4 (N=94) **MEAN (SD)**	NON-ADHD: STUDY AIMS 5 & 6 (N=37) **MEAN (SD)**	ADHD (N=38) **MEAN (SD)**
Attention (possible range: 5-20)	9.91 (2.40)	9.24 (2.47)	13.87 (2.68)
Cognitive Instability (possible range: 3-12)	6.15 (1.75)	5.92 (1.94)	8.05 (1.94)
Attention Total (possible range: 8-32)	16.06 (3.43)	15.16 (3.63)	21.92 (4.02)
Motor (possible range: 7-28)	14.20 (3.16)	14.68 (3.07)	17.18 (4.24)
Perseveration (possible range: 4-16)	6.61 (1.27)	6.38 (1.34)	7.53 (1.74)
Motor Total (possible range: 11-44)	20.81 (3.67)	21.05 (3.84)	24.71 (5.19)
Self-Control (possible range: 6-24)	11.81 (3.00)	11.57 (2.66)	15.01 (3.61)
Cognitive Complexity (possible range: 5-20)	11.05 (2.26)	10.70 (2.60)	12.37 (2.95)
Non-Planning Total (possible range: 11-44)	22.86 (4.44)	22.27 (4.59)	27.38 (5.18)
BIS-11 Total Score (possible range: 30-120)	59.84 (8.27)	58.49 (8.87)	74.01 (12.35)

Table 5: BIS-11 scores by diagnostic group.

BIS-11 FACTOR- **ADHD PARTICIPANTS ONLY**	ADHD- ON MEDS DURING TESTING N=17 **MEAN (SD)**	ADHD- NO MEDS DURING TESTING N=21 **MEAN (SD)**	STATISTIC
Attention (possible range: 5-20)	13.94 (3.51)	13.81 (1.86)	*t(*36)=0.15; *p*=.883
Cognitive Instability (possible range: 3-12)	8.12 (2.15)	8.00 (1.82)	*t(*36)=0.18; *p*=.856
Attention Total (possible range: 8-32)	22.06 (4.99)	21.81 (3.16)	*t(*36)=0.19; *p*=.852
Motor (possible range: 7-28)	16.47 (4.27)	17.76 (4.23)	*t(*36)=-0.93; *p*=.358
Perseveration (possible range: 4-16)	7.35 (1.84)	7.67 (1.68)	*t(*36)=-0.55; *p*=.587
Motor Total (possible range: 11-44)	23.82 (5.07)	25.43 (5.30)	*t(*36)=-0.95; *p*=.350
Self-Control (possible range: 6-24)	13.85 (4.31)	15.95 (2.69)	*t(*36)=-1.84; *p*=.075
Cognitive Complexity (possible range: 5-20)	12.18 (3.26)	12.52 (2.73)	*t(*36)=-0.36; *p*=.723
Non-Planning Total (possible range: 11-44)	26.03 (5.67)	28.48 (4.60)	*t(*36)=-1.47; *p*=.150
BIS-11 Total Score (possible range: 30-120)	71.91 (14.23)	75.71 (10.64)	*t(*36)=-0.94; *p*=.352

Table 6: BIS-11 scores within ADHD groups.

A one-way ANOVA was used to determine if BIS-11 scores for each subfactor (i.e., attention, cognitive instability, motor, perseveration, self-control, cognitive complexity), factor (i.e., attention total, motor total, non-planning total), and total score differed by diagnostic group for the participants used in study aims 1-4. Please see tables above for descriptive data. Results of the ANOVA revealed significant differences for all factors: attention *F(*2,129)=34.051, *p*=.000; cognitive instability *F*(2,129)=14.950, *p*=.000; motor *F*(2,129)=10.482, *p*=.000; perseveration *F*(2,129)=11.913, *p*=.004; self-control *F*(2,129)=16.086, *p*=.000; cognitive complexity *F*(2,129)=3.892, *p*=.023; attention total *F*(2,129)=35.459, *p*=.000; motor

total $F(2,129)=12.650$; $p=.000$; non-planning total $F(2,129)=14.199$. $p=.000$; and total score: $F(2,129)=30.279$, $p=.000$. Post-hoc testing using the Bonferroni correction for multiple comparisons found that participants without ADHD endorsed significantly lower levels of each factor than both the ADHD on medication and ADHD off medication groups, all $p=.000$. There were no significant differences in ASRS scores within the ADHD group depending on medication status, all $p>.05$.

For the subset of participants analyzed in study aims 5 & 6, the findings were consistent with the patterns above. Specifically, a one-way ANOVA found differences between diagnostic groups for all BIS-11 variables: attention $F(2,72)=29.780$, $p=.000$; cognitive instability $F(2,72)=11.209$, $p=.000$; motor $F(2,72)=4.859$, $p=.010$; perseveration $F(2,72)=5.265$, $p=.007$; self-control $F(2,72)=13.636$, $p=.000$; cognitive complexity $F(2,72)=3.396$, $p=.039$; attention total $F(2,72)=28.801$, $p=.000$; motor total $F(2,72)=6.590$, $p=.000$; non-planning total $F(2,72)=11.598$, $p=.000$; and total score $F(2,72)=20.107$, $p=.000$. Post-hoc testing using the Bonferroni correction for multiple comparisons found that participants without ADHD endorsed significantly lower levels of each factor than both the ADHD on medication and ADHD off medication groups, all $p=.000$.

5.3 Randomization to Metronome Group

Study Aims 1-4 (N=132). To ensure no systematic differences across the two metronome conditions and the three diagnostic groups for age and intellectual level,

measured by Matrix Reasoning raw score, after randomization, a 2 (metronome condition) by 3 (diagnostic group) ANOVA was conducted for each variable. Age of participants did not differ across diagnostic groups: $F(2,126)=0.267$, $p=.766$; or by metronome condition: $F(1,126)=0.016$, $p=.901$. There was a trend for Matrix Reasoning raw scores to differ by diagnostic group: $F(2,126)=2.935$, $p=.057$; but scores did not significantly differ by metronome condition: $F(1,126)=0.048$, $p=.927$. Specifically, mean Matrix Reasoning raw score for the no ADHD group was 20.64 (SD=3.826); ADHD on medication mean was 19.18 (SD=3.957), and ADHD off medication was 19.95 (SD=3.776). Because of this trend, Matrix Reasoning raw score was used as a covariate where indicated. Post-hoc testing using the Bonferroni correction revealed that the control group reported fewer ASRS symptoms of hyperactivity/impulsivity than either ADHD group, with no significant difference in levels of hyperactivity/impulsivity within the ADHD group. There was also no significant interaction between diagnostic group and metronome condition for either age: $F(2,126)=0.272$, $p=.762$ or Matrix Reasoning raw score: $F(2,126)=0.012$, $p=.988$.

Chi-squared tests found no differences in handedness or gender across the three diagnostic groups or two metronome groups: gender distribution by metronome condition: $X^2(1)=0.327$, $p=.597$; gender distribution by ADHD group: $X^2(2)=3.918$, $p=.141$; handedness distribution by metronome condition: $X^2(1)=0.255$, $p=.613$; handedness distribution by ADHD group: $X^2(2)=3.500$, $p=.174$.

To ensure no systematic differences across the two metronome conditions and the three diagnostic groups for ASRS symptoms of inattentiveness and hyperactivity/impulsivity, a 2 (metronome condition) by 3 (diagnostic group) ANOVA was conducted for each variable. There was no main effect of metronome condition on ASRS score: $F(1,126)=0.297$, $p=.587$. There was a main effect of diagnostic group on inattentiveness symptoms on the ASRS: $F(2,126)=43.141$, $p=.000$. Post-hoc testing using the Bonferroni correction confirmed that the control group reported fewer ASRS symptoms of inattentiveness than either ADHD group, with no significant difference in levels of inattentiveness within the ADHD group. This confirmed that the diagnostic groups continued to differ on this measure after randomization. The interaction between diagnostic group and metronome condition for ASRS inattentiveness approached significance: $F(2,126)=2.973$, $p=.055$. Post-hoc testing using the Bonferroni correction revealed that for controls, ASRS scores did not differ by metronome assignment. However, for participants with ADHD currently on medication, mean ASRS score for those assigned to the slow metronome trended higher than scores of those assigned to the fast metronome; this trend was reversed for participants with ADHD off medication. Specifically, the mean ASRS inattentiveness score for ADHD participants on medication assigned to the slow condition was 20.00, SD=5.92. The mean ASRS inattentiveness score for the same clinical group assigned to the fast condition was 24.50, SD=4.90. For those with ADHD not currently on medication, mean ASRS inattentiveness in those assigned to

the slow condition was 23.64, SD=6.19; the mean ASRS inattentiveness for this clinical group assigned to the fast condition was 21.10, SD=3.64. All ADHD groups remained in the "likely to have ADHD" classification based on mean ASRS scores.

A 2 (metronome condition) by 3 (diagnostic group) ANOVA was conducted for ASRS hyperactivity/impulsivity as well. There was no main effect of metronome condition on ASRS hyperactivity/impulsivity: $F(1,126)=0.129$, $p=.720$. There was a main effect of diagnostic group on hyperactivity/impulsivity symptoms on the ASRS: $F(2,126)=29.422$, $p=.000$. Post-hoc testing using the Bonferroni correction confirmed that the control group reported fewer ASRS symptoms of hyperactivity/impulsivity than either ADHD group, with no significant difference in levels of hyperactivity/impulsivity within the ADHD group. This confirmed that the diagnostic groups continued to differ on this measure after randomization. There was no significant interaction between diagnostic group and metronome condition for ASRS hyperactivity/impulsivity: $F(2,126)=0.983$, $p=.377$.

See tables below for means of these measures by metronome group.

PARTICIPANTS: STUDY AIMS 1-4: MEAN ASRS INATTENTIVENESS (SD)		
DIAGNOSTIC GROUP	SLOW METRONOME GROUP N=67	FAST METRONOME GROUP N=65
No ADHD (N=94)	14.38 (4.15)	14.11 (4.24)
ADHD- on medication (N=17)	20.00 (5.92)	24.50 (4.90)
ADHD- off medication (N=21)	23.64 (6.19)	21.10 (3.64)

Table 7: ASRS inattentiveness by diagnostic and metronome groups.

PARTICIPANTS: STUDY AIMS 1-4: MEAN ASRS HYPERACTIVITY/IMPULSIVITY (SD)		
DIAGNOSTIC GROUP	SLOW METRONOME GROUP N=67	FAST METRONOME GROUP N=65
No ADHD (N=94)	11.79 (4.75)	10.11 (4.82)
ADHD- on medication (N=17)	18.33 (8.79)	20.50 (4.00)
ADHD- off medication (N=21)	19.09 (6.52)	17.30 (5.60)

Table 8: ASRS hyperactivity/impulsivity by diagnostic and metronome groups.

Study Aims 5-6 (N=75). To ensure no systematic differences across the two metronome conditions and the three diagnostic groups for age and Matrix Reasoning performance after randomization for the participants in study aims 5 and 6, a 2 (metronome condition) by 3 (diagnostic group) ANOVA was conducted for each variable. For age, there was no main effect of metronome condition: $F(1,69)=.075$, $p=.785$, nor any main effect of diagnostic group: $F(2,69)=.106$, $p=.900$. There was also no significant interaction between diagnostic group and metronome condition for age: $F(2,69)=0.388$, $p=.680$.

PARTICIPANTS: STUDY AIMS 1-4: MEAN MATRIX REASONING RAW SCORE (SD)		
DIAGNOSTIC GROUP	SLOW METRONOME GROUP N=67	FAST METRONOME GROUP N=65
No ADHD (N=94)	20.47 (3.73)	20.81 (3.95)
ADHD- on medication (N=17)	18.00 (4.36)	18.00 (7.95)
ADHD- off medication (N=21)	19.82 (4.40)	20.10 (1.73)

Table 9: Matrix Reasoning raw scores by diagnostic and metronome groups.

For Matrix Reasoning, raw scores did not significantly differ by metronome condition: $F(1,69)=0.325$, $p=.570$. There was, however, a trend toward a main effect of diagnostic group on Matrix Reasoning raw score: $F(2,69)=3.852$, $p=.086$. There was no significant interaction between diagnostic group and metronome condition for Matrix Reasoning raw score: $F(2,69)=0.540$, $p=.585$. Post-hoc testing using the Bonferroni correction found that participants without ADHD compared with ADHD participants who had taken their medication that day did not significantly differ, $p=.101$; all other pairwise comparisons were not significant at higher p values. However, due to a trend toward significance, Matrix reasoning score was used as a covariate where appropriate in subsequent analyses.

Chi-square tests found no differences in handedness or gender across the three diagnostic groups or two metronome conditions: gender distribution by metronome condition: $X^2(1)=.017$, $p=.896$; gender distribution by diagnostic group: $X^2(2)=2.330$, $p=.312$; handedness distribution by metronome condition: $X^2(1)=0.668$, $p=.414$; and handedness distribution by diagnostic group: $X^2(2)=3.976$, $p=.137$.

To ensure no systematic differences across the two metronome conditions and the three diagnostic groups for ASRS symptoms of inattentiveness and hyperactivity/impulsivity for study aims 5 and 6, a 2 (metronome condition) by 3 (diagnostic group) ANOVA was conducted for each variable. There was a main effect of diagnostic group on inattentiveness symptoms on the ASRS: $F(2,69)=21.685$,

p=.000, with the ADHD groups reporting more symptoms of inattention. ASRS inattentive symptoms did not significantly differ by metronome condition: *F(*1,69)=0.777, *p*=.381. There was a trend for an interaction between diagnostic group and metronome condition for ASRS inattentiveness: *F(*2,69)=2.637, *p*=.079. This is the same trend and same participants from studies 1-4, again showing that for participants with ADHD currently on medication, mean ASRS score for those assigned to the slow metronome trended lower than scores of those assigned to the fast metronome; this trend was reversed for participants with ADHD off medication. The means of both ADHD groups, however, remained in the "likely to have ADHD" category based on ASRS cutoffs.

A 2 (metronome condition) by 3 (diagnostic group) ANOVA was conducted for ASRS hyperactivity/impulsivity symptoms as well for groups used in study aims 5 and 6. There was a main effect of diagnostic group on hyperactivity/impulsivity symptoms: *F*(2,69)=24.696, *p*=.000. Post-hoc testing using the Bonferroni correction revealed that the control participants reported fewer hyperactive/impulsive symptoms on the ASRS than either ADHD group, and that the two ADHD groups (on medication and off) did not significantly differ from each other on this measure. ASRS hyperactivity/impulsivity did not differ significantly by metronome condition: *F*(1,69)=0.083, *p*=.774. There was no significant interaction between diagnostic group and metronome condition for ASRS hyperactivity/impulsivity: *F*(2,69)=0.809, *p*=.449.

See tables below for means of these measures by metronome group.

PARTICIPANTS: STUDY AIMS 5&6: MEAN ASRS INATTENTIVENESS (SD)		
DIAGNOSTIC GROUP	SLOW METRONOME GROUP N=38	FAST METRONOME GROUP N=37
No ADHD (N=37)	14.61 (3.91)	15.68 (4.22)
ADHD- on medication (N=17)	20.00 (5.92)	24.50 (4.90)
ADHD- off medication (N=21)	23.64 (6.19)	21.10 (3.64)

Table 10: ASRS inattentiveness scores by diagnostic group and metronome condition (study aims 5&6).

PARTICIPANTS: STUDY AIMS 5&6: MEAN ASRS HYPERACTIVITY/IMPULSIVITY (SD)		
DIAGNOSTIC GROUP	SLOW METRONOME GROUP N=38	FAST METRONOME GROUP N=37
No ADHD (N=37)	10.78 (3.56)	9.26 (4.45)
ADHD- on medication (N=17)	18.33 (8.79)	20.50 (4.00)
ADHD- off medication (N=21)	19.09 (6.52)	17.30 (5.60)

Table 11: ASRS hyperactivity / impulsivity scores by diagnostic group and metronome condition (study aims 5 & 6).

5.4: Results for Study Aims

STUDY AIM 1: To establish if feedback from a device regarding the length of a second can influence temporal duration estimations.

- Hypothesis: Feedback from a false metronome will affect brief (20 sec) time interval estimates in the following ways: active feedback training to 50 beats per minute (bpm), but labeled as 60 bpm / 1 beat per second, will induce under-estimations of brief time intervals. Active feedback training to 70 bpm (labeled also as 60 bpm / 1 beat per second) will induce over-estimations of time intervals.

A 2 (metronome condition) by 3 (diagnostic group) by 5 (trial) repeated measures ANOVA was used with metronome condition (slow, fast) and diagnostic status (no ADHD, ADHD on medication, ADHD off medication) as the between subjects measures, and trial number (baseline, T1, T2, T3, and delay) as the repeating measure within subjects. This test was run with a Greenhouse-Geisser correction due to Mauchly's Test of Sphericity being violated: $X^2(9)=209.793$, $p=.000$.

Results of this ANOVA determined that there was a significant main effect of trial number on mean time estimation: $F(2.176, 271.948) = 4.622$, $p=.009$. There was a main effect of metronome speed on mean time estimation across trials: $F(1.088, 271.958)=161.208$, $p=.000$. There was no main effect of diagnostic group on mean time estimation $F(2.176, 271.948)=0.070$, $p=.934$. There was a significant interaction effect between metronome condition and trial number on mean time estimation across trials: $F(2.176, 271.948) = 30.059$, $p=.000$. There was no significant interaction between trial number and diagnostic group on time estimations: $F(4.351, 271.948)=0.612$, $p=.668$. There was no significant three-way interaction between trial number, metronome speed, and diagnostic group on time estimations: $F(4.351, 271.948)=1.165$, $p=.327$.

Post-hoc tests using the Bonferroni correction revealed that time estimations collapsed across diagnostic group differed between the metronome conditions at training trials 1, 2, 3, and the delay, but not at baseline (see figure and table below

for results), with participants assigned to the slow metronome group over-producing 20 second time intervals, and participants assigned to the fast metronome group under-producing 20 second time intervals.

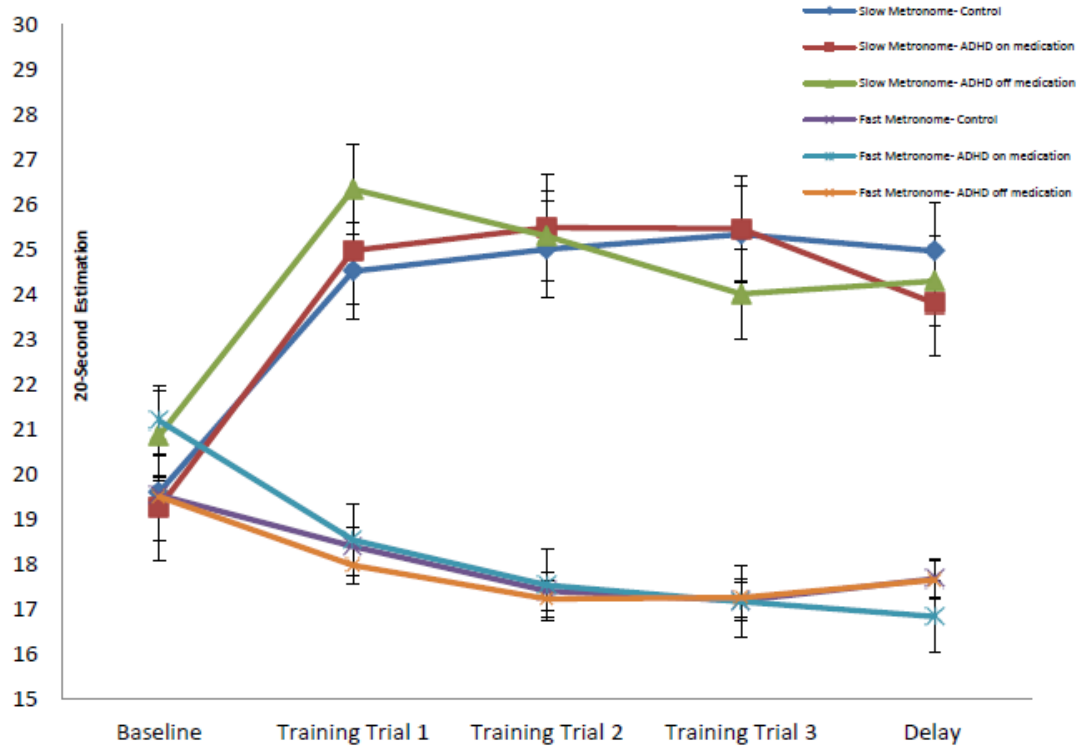


Figure 3: Time estimations over trials by diagnostic group and metronome condition.

	BASELINE ESTIMATION MEAN SECONDS (SD)	**TRIAL 1 EST.** MEAN SECONDS (SD)	**TRIAL 2 EST.** MEAN SECONDS (SD)	**TRIAL 3 EST.** MEAN SECONDS (SD)	**DELAY EST.** MEAN SECONDS (SD)
Slow Metronome	19.76 (5.54)	24.88 (4.33)	25.12 (2.47)	25.14 (2.68)	24.71 (2.94)
Fast Metronome	19.72 (3.72)	18.33 (1.54)	17.41 (1.12)	17.26 (1.20)	17.65 (2.30)
Corrected t-value between S and F groups (df); p value	0.050 (130); .960	11.5109 (130); .000	22.960 (130); .000	21.608 (130); .000	15.246 (130); .000

Table 12: Time estimations by metronome condition collapsed across diagnostic group.

Removing the participants without a diagnosis of ADHD who scored above threshold on the ASRS for inattentiveness and/or hyperactivity/impulsivity did not alter the patterns of significance for the above findings.

Metronome Training Trials- Learning and Duration.

In general, participants were easily oriented to the manipulation and most required only 3 training trials to reach criteria (3 trials with estimations greater than or equal to 22 seconds for the slow group, 3 trials with estimations less than or equal to 18 seconds for the fast group). Only 12 of 132 participants (9.1%) required more than 3 training trials to reach criteria. Of those 12 participants, 9 required one additional training trial, 2 required two additional trials, and one participant required five additional trials. A 2 (metronome condition) by 3 (diagnostic group) ANOVA found that there was no main effect of metronome condition on number of trials required to reach criteria: $F(1,126)=0.360$; $p=.550$. There was also no main effect of diagnostic group on number of training trials required to reach criteria: $F(2,126)=1.217$; $p=.300$. There was no significant interaction between diagnostic group and metronome condition on number of trials required to reach criteria: $F(2, 126)=0.815$, $p=.445$.

However, within the ADHD group, a Bonferroni-corrected post hoc test found that participants who did not take their prescribed ADHD medication the day of testing required more trials to reach criteria, requiring a mean of 3.24 trials

(*SD*=.437) compared to those on ADHD medication, who required a mean of 3.00 trials (*SD*=.000). Due to the small number of participants in both these groups who required more than 3 trials, equal variances were not assumed for that analysis: *t(*16)=-2.219; *p*=.041.

Immediately preceding debriefing, participants were asked to rate on a scale of 1 to 5 how confident they were the metronome condition they had been training to was accurate (i.e., beating at 60 beats per minute). A rating of 1 was equivalent to definitely thinking it was not accurate, and a 5 equivalent to definitely thinking is was accurate. 74% of participants thought the metronome was "definitely" or "probably" accurate. The median response was a 4. Participants were equally likely to believe the metronome was accurate regardless of metronome condition group: *t(*130)=-.383; *p*=.703.

RATING	PERCENTAGE
1: Definitely thought it was not accurate	2.9
2: Thought it was probably not accurate	12.9
3: Chances of it being accurate 50/50	10.1
4: Thought it was probably accurate	46.8
5: Definitely thought it was accurate	27.3

Table 13: Ratings of belief in metronome accuracy.

Estimations of longer amounts of time (i.e., time spent on the delay discounting task and time spent on the Matrix Reasoning task) were elicited as well, with no cueing that we would be asking for these estimations. To determine if the

metronome training had an impact on longer time estimations a 2 (metronome condition) by 3 (diagnostic group) ANCOVA with time estimation for the delay discounting task serving as the dependent variable and the actual time spent on the task as the covariate was completed. There was no main effect of the covariate, actual length of time spent on the delay discounting task, on delay discounting time estimations: $F(1,125)=1.270$, $p=.262$. There was no main effect of metronome condition on delay discounting estimations: $F(1,125)=0.271$, $p=.604$. There was also no main effect of ADHD group on delay discounting estimations when controlling for actual length of task: $F(2,125)=1.565$, $p=.213$. There was also no interaction between metronome condition and diagnostic group on delay discounting estimations when controlling for actual length of task: $F(2,125)=0.191$, $p=.827$. Levene's test for homogeneity of variance found no difference in variances of estimations between the diagnostic groups, $F(2,129)=0.925$, $p=.399$.

Similarly, a 2 (metronome condition) by 3 (ADHD group) ANCOVA was used for time estimations for the Matrix Reasoning test with metronome condition and diagnostic group as the independent variables, estimation of time (seconds) spent on the delay Matrix Reasoning as the dependent variable, and time actually spent on the Matrix Reasoning task as a covariate. There was a significant main effect of the covariate, length of time actually spent on the Matrix Reasoning task, and estimations of time spent on it: $F(1,125)=44.090$, $p=.000$. There was no main effect

of metronome condition on Matrix Reasoning estimations when controlling for actual length of task: $F(1,125)=0.003$, $p=.956$. There was also no main effect of ADHD group status on Matrix Reasoning estimations when controlling for actual length of task: $F(2,125)=0.184$, $p=.832$. There was also no interaction between metronome condition and diagnostic group on Matrix Reasoning estimations when controlling for actual length of task: $F(2,125)=0.447$, $p=.641$. Levene's test for homogeneity of variance found no difference in variances of estimations between the diagnostic groups, $F(2,129)=1.357$, $p=.261$.

Removing the participants in the no-ADHD group who scored above threshold on the ASRS for inattentiveness and/or hyperactivity/impulsivity did not alter the patterns of significance for the above findings.

STUDY AIM 2: To determine if this manipulation of local temporal perception affects rates of delay discounting.

- Hypothesis: Those who have been trained with the slow tempo (50 bpm) will show decreased rates of delay discounting in a delay discounting task with respect to those trained with the fast tempo (70 bpm).

STUDY AIM 3: To explore how this manipulation of local temporal perception affects delay discounting in an ADHD population.

- Hypothesis: The clinical ADHD group will exhibit delay discounting patterns similar to the non-ADHD group in response to the metronome training, but the effect will be smaller due to inherent greater variability of temporal perception in the ADHD group.

The above two aims are combined in following analyses. Mean *k* for the entire sample (N=132) was .0389, with .0022 standard deviation. The observed range of *k* was 0 to .0944. Skewness was 0.743, with 0.211 standard error. A 2 (metronome condition) by 3 (diagnostic group) ANOVA was used to determine how *k* may be affected by these variables. There was no main effect of metronome condition on *k*: $F(1,126)=.024$, $p=.878$. There was no main effect of ADHD group on *k*: $F(2,126)=0.757$, $p=.471$. There was no interaction between metronome condition and ADHD group: $F(2,126)=.343$, $p=.709$. The mean *k* of the slow group was .0378, *SD*=.0254; mean *k* of the fast group=.0399, *SD*=.0265 (see figures below). Removing the participants in the No-ADHD group who scored above threshold on the ASRS for inattentiveness and/or hyperactivity/impulsivity did not alter the patterns of significance for the above findings. Please see Appendix F for *k* convergence curves for each diagnostic and metronome group.

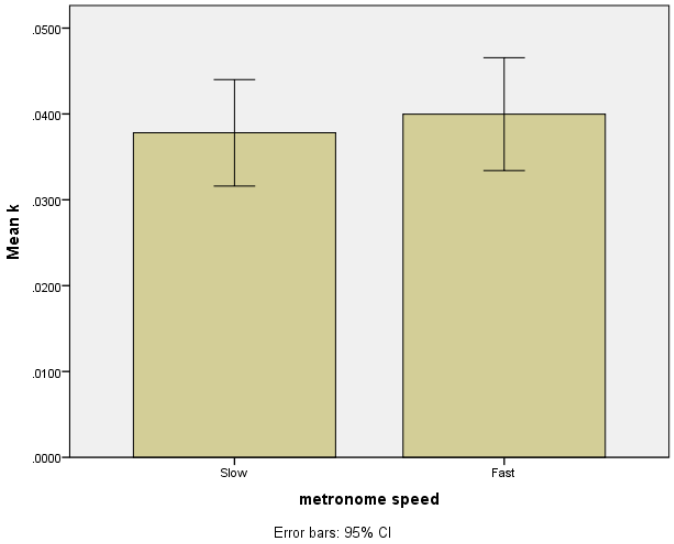


Figure 4: *K* by metronome condition, collapsed across diagnostic groups.

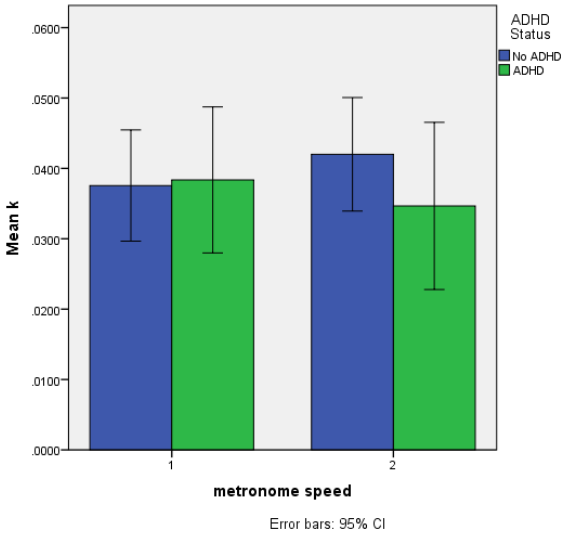


Figure 5: K by metronome condition and diagnostic group.

A multiple linear regression examining effects of ADHD symptoms (i.e., scores on the ASRS Inattentiveness and Impulsivity/Hyperactivity subscales) was used to examine any effects on *k*. ASRS total scores for each of the two subscales were

entered together into the regression. ADHD symptoms on the ASRS did not significantly predict k: $F(2,129)=0.858$, $p=.426$, $R^2=.013$.

A post-hoc Bonferroni-corrected t-test examining the effects on *k* of those who reported they "definitely" or "probably" believed the metronome was accurate vs. those who did not found no significant difference between the two groups, $t(130)=-1.539$; $p=.126$.

STUDY AIM 4: To explore the role self-reported impulsivity may be playing in the relationship between manipulated temporal perception and delay discounting.

- Hypothesis: Higher levels of trait impulsivity in all groups will be associated with higher rates of delay discounting, with high impulsivity and exposure to fast metronome correlated with steepest delay discounting.

Mean BIS-11 score for the entire sample (N=132) was 63.92 (*SD*=11.53); the range was 44-102. Although no established clinical cut off scores exist in the literature for the BIS-11, other studies have suggested the use of the 75th percentile score for high impulsivity (Malone et al., 2009). In the current study, a quartile analysis showed this top cutoff was at score 71. Participants above this value were considered "high impulsivity" for the purposes of this analysis (n=30). The bottom

quartile cut off score was at 57. Participants below this value were considered "low impulsivity" for the purposes of this analysis (n=31).

A 2 (high impulsivity vs low impulsivity) by 2 (metronome condition) ANOVA was used with the sample of 61 participants who fell into either high or low quartiles of impulsivity to examine effects on dependent variable *k*. The high impulsivity group consisted of nine control participants, nine participants with ADHD on medication, and twelve participants with ADHD off medication. The low impulsivity group consisted of thirty control participants and one participant with ADHD on medication. There was no main effect of impulsivity on *k*: $F(1,57)=0.200$, $p=.656$. Within this sample, there was also no main effect of metronome condition on *k*: $F(1,57)=0.055$, $p=.815$. There was also no significant interaction between impulsivity and metronome condition on *k*: $F(1,57)=2.140$, $p=.149$.

BIS-11 total score for the entire sample of participants (N=132) was not correlated with *k*, Pearson correlation=0.005; $p=.954$. This was also true when the ADHD sample was examined independently, Pearson correlation=0.119; $p=.477$.

A multiple regression was used on the entire sample of participants to predict *k* from the three subscales of the BIS-11 entered together (attention, motor, and non-planning). These variables did not significantly predict *k*, $F(3,128) = 0.670$, $p=.572$, $R^2= .015$.

STUDY AIM 5: To determine if working memory and processing speed capacity have a significant influence on delay discounting.

- Hypothesis: Working memory capacity will have a significant influence on delay discounting; specifically, lower working memory capacity will be associated with increased delay discounting rates. Processing speed capacity will have a significant influence on delay discounting; specifically, slower processing speed will be associated with increased delay discounting rates.

For this study aim, all analyses were performed on the subset of the total participants who received these cognitive measures (N=75: 37 no-ADHD participants, 17 ADHD on medication, 21 ADHD off medication). See following page for results.

Performance measures and ADHD status.

Cognitive Measure	Non-ADHD N=37 Mean (SD)	ADHD (currently on medication N=17) Mean (SD)	ADHD (NOT currently on medication N=21) Mean (SD)	ADHD total N=38 Mean (SD)
Color Naming Time-seconds (Primary Measure)	20.81 (2.73)	22.32 (2.89)	23.03 (8.37)	21.36 (3.07)
Symbol Search # correct (Primary Measure)	40.49 (7.28)	40.24 (8.34)	35.65 (6.75)	37.81 (7.70)
Digit span total score (Primary Measure)	29.18 (5.04)	28.71 (4.46)	29.00 (4.85)	28.95 (4.74)
Longest Digit span forward	6.55 (1.15)	7.24 (1.20)	7.04 (1.08)	7.13 (1.17)
Longest Digit span back	5.13 (1.27)	4.71 (0.92)	4.96 (1.23)	4.87 (1.12)
Longest Digit span sequenced	6.55 (1.36)	6.24 (1.09)	6.32 (1.26)	6.13 (1.17)
Longest digits forward - longest digits back	*1.18 (2.26)	2.41 (1.58)	2.13 (0.95)	*2.24 (1.26)
N-back task-total correct of 100 (Primary Measure)	*79.03 (8.29)	74.71 (10.14)	73.76 (12.58)	*74.18 (11.41)

Table 14: Cognitive measures by diagnostic group.
*= significant difference between groups at the $p<.05$ level.

The above table shows a summary of the cognitive data. The primary processing speed measures used in subsequent analyses were color naming time

(seconds) and Symbol Search number correct in 120 seconds. Performance on these two measures were not significantly correlated, Pearson's $r(75)= 0.191$; $p=.106$. The primary working memory measures used in subsequent analyses were n-back total items correct of 100 and digit span total score. These two measures were significantly correlated, Pearson's $r(75)=0.329$, $p=.004$.

An ANOVA was used to examine any group differences in mean performances with regard to each of the cognitive measures individually (see table above). No significant differences were found between the three diagnostic groups, all $p>.05$. However, when medication status was collapsed across the ADHD group, there were significant differences between controls and ADHD participants on longest digits forward minus longest digits back, as well as the N-back task. Bonferroni-corrected post-hoc testing revealed that the control participants had a smaller difference between digits forward and digits back, as well as more items correct on the N-back task.

Removing the participants in the No-ADHD group who scored above threshold on the ASRS for inattentiveness and/or hyperactivity/impulsivity for the above measures found only one significant difference between groups, a difference on symbol search number correct: $F(2,58)=3.579$, $p=.034$. Specifically, when removing these participants from analysis, people with ADHD not currently on medication performed worse on symbol search than those without ADHD and those with ADHD on medication.

Medication status was then collapsed within the ADHD group and differences were examined between the ADHD and non-ADHD groups on these measures. The difference between longest digits forward and longest digits back was larger within the ADHD group as compared with the non-ADHD group: $F(1, 73)=5.063$, $p=.027$. Additionally, those without ADHD performed significantly better on the N-back task than those with ADHD: $F(1, 72)=4.206$, $p=.044$). This finding remained significant when the participants without a diagnosis of ADHD who scored above threshold on the ASRS for inattentiveness and/or hyperactivity/impulsivity were removed.

A multiple linear regression was performed to predict *k* from the four main cognitive measures entered together (N-back score and digit span total score for working memory; and color naming time and Symbol Search number correct for processing speed), while controlling for any effects of Matrix Reasoning raw score. Matrix Reasoning raw score failed to predict k: $F(1,69)1.221$, $p=.273$, $R^2=.017$. These four main cognitive variables did not significantly predict *k*, controlling for Matrix Reasoning score: $F(5,65) = 1.093$, $p=.373$, $R^2= .078$.

Because only N-back and digits forward minus digits back were significantly different between the ADHD and non-ADHD groups (as well as symbol search once ADHD-like controls were removed), these three variables were entered together as variables in a multiple regression analysis to examine impact on variable *k*. The multiple linear regression analysis found that neither of the independent or

combined factors have relevant explanatory power on *k*: $F(3,71)=0.467$, $p=.706$. $R^2=.020$.

STUDY AIM 6: To explore how working memory capacity and processing speed affects timing training to a metronome.

- Hypothesis: Working memory capacity will influence time estimation. Specifically, lower working memory capacity will be associated with
    - less accurate time estimations of both short-term and long-term time intervals
    - more training trials needed to reach criterion on metronome task
- Hypothesis: Processing speed capacity will influence time estimation. Specifically, slower processing speed will be associated with
    - less accurate time estimations of both short-term and long-term time intervals
    - more training trials needed to reach criterion on metronome task

For these study aims, all analyses were performed on the subset of the total participants who received these cognitive measures (N=75).

Working memory. Two-tailed correlational analyses were performed to examine the relationship between the two primary working memory variables (digit span total

score and N-back performance) and absolute value of deviation of baseline time estimation of 20 seconds (before exposure to the metronome) from 20 seconds (henceforth referred to as "short-term accuracy"). Digit span total score was not correlated with short-term accuracy of baseline time estimation: $r(75)=-0.88$, $p=.451$; nor was performance on the N-back task: $r(75)=-0.031$, $p=.795$.

To examine the relationship between working memory on longer time duration estimations, two-tailed correlational analysis were performed to examine the relationship between digit span total score and N-back performance and absolute value of deviation of estimation of time spent on the delay discounting task from actual time spent on it (henceforth referred to as "long-term accuracy"). The results of this analysis indicated that digit span performance is not related to long-term accuracy, $r(72)=-0.122$, $p=.300$. The same analysis was performed with N-back performance in place of digit span total score and also found no relationship between N-back performance and long-term accuracy: $r(71)=-.064$, $p=.593$.

Correlations were performed between digit span total performance and long-term accuracy of time estimates for the Matrix Reasoning task as well. The results of this correlational analysis indicated that digit span performance is not related to long-term accuracy for the Matrix Reasoning task: $r(72)=0.185$, $p=.115$. N-back performance was also not related to long-term accuracy for the Matrix Reasoning task: $r(71)=0.005$, $p=.969$.

Neither total digit span performance nor N-back performance were correlated with number of training trials required to reach criteria during the metronome training: digit span $r(75)=0.195$, $p=.093$; N back $r(74)=.012$, $p=.921$.

Processing Speed. Two-tailed correlational analyses were performed to examine the relationship between the two primary performance speed variables (Color Naming time and Symbol Search number correct) and short-term accuracy of baseline estimation. Digit span total score was not correlated with short-term accuracy of baseline time estimation: $r(75)=.043$, $p=.716$; nor was performance on the Symbol Search task: $r(75)=0.148$, $p=.213$.

With regard to processing speed and longer time duration estimations, two-tailed correlational analyses found no relationship between Color Naming time and long-term accuracy on the delay discounting task, $r(72)=0.064$, $p=.586$, nor long-term accuracy on the Matrix Reasoning task, $r(72)=-0.119$, $p=.311$. The same analyses were performed with Symbol Search performance in place of Color Naming time. There was no relationship between Symbol Search performance and long-term accuracy on the delay discounting task, $r(70)=-.026$, $p=.825$; nor long-term accuracy on the Matrix Reasoning task, $r(70)=0.009$, $p=.941$.

Neither Color Naming time nor Symbol Search performance were correlated with number of training trials required to reach criteria during the metronome training, Color Naming: $r(75)=0.031$, $p=.789$; Symbol Search: $r(74)=.012$, $p=.921$.

In addition to examining the relationships between these cognitive measures and baseline short-term accuracy, possible relationships between the cognitive measures and baseline estimation response value (i.e., the actual time at which the participant indicated 20 seconds has elapsed) were explored as well. These analyses focused on the relationship on perception of length of time of 20 seconds, rather than deviation from the "correct" response. A correlational analysis found that total digit span performance was related to baseline time estimation, $r(75)=.245$, $p=.028$. Removal of a single outlier from the ADHD on medication group (estimation of 20 seconds was 44 seconds, more than 3 standard deviations from the mean) improved this relationship: $r(74)=.293$, $p=.011$ (see figure on next page).

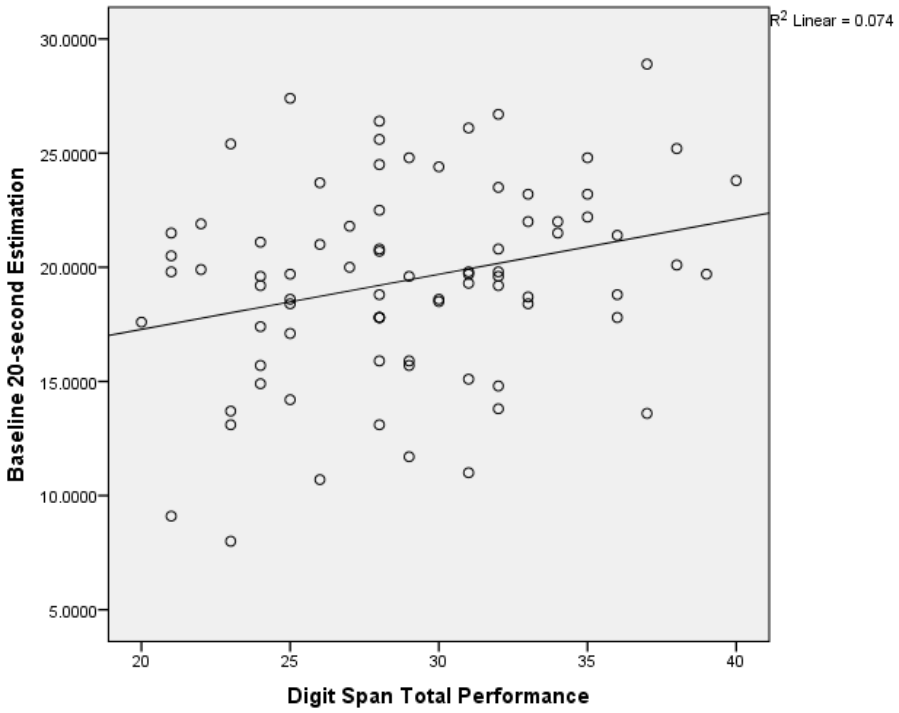


Figure 6: Relationship between Digit Span total performance and baseline 20-second estimation.

Performance on the N-back task was not correlated with baseline estimation, *r(*74)=.109; *p*=.357, nor was Symbol Search performance, *r(*75)=.080, *p*=.080. There was, however, a trend toward a relationship between Color Naming time and baseline estimation, *r*(75)=-.217, *p*=.062, with faster performance on Color Naming trending toward a correlation with longer baseline estimations. However, this trend weakened with removal of a single outlier from the ADHD group not currently on medication whose Color Naming time (30 seconds) was more than three standard deviations from the mean, *r*(74)=-.191, *p*=.103.

Relationships between the cognitive variables and estimations of longer time durations were examined as well in correlational analyses. With regard to working memory, N-back performance was not correlated with time estimations of duration of the Matrix Reasoning task: $r(74)=.034$, $p=.771$; nor delay discounting task: $r(74)=-.164$, $p=.163$. Digit span performance was not correlated with delay discounting task time estimation, $r(75)=.026$, $p=.828$.

Digit span total performance was correlated with Matrix Reasoning time estimation: $r(75)=.264$, $p=.022$, though a partial correlation analysis found this relationship was partially accounted for by Matrix Reasoning raw score: $r(72)=0.197$, $p=.136$.

With regard to processing speed, performance on Symbol Search was correlated with neither estimations of longer durations of time on the Matrix Reasoning task: $r(70)=.084$, $p=.483$; nor delay discounting task, $r(72)=.030$, $p=.802$. Performance on the color naming task was correlated with neither Matrix Reasoning time estimation*:* $r(72)=-.024$, $p=.840$; nor delay discounting task time estimation: $r(72)=.122$, $p=.300$.

Chapter 6: Discussion

Timing Manipulation. The findings of the current study suggest that it is possible to use a simple manipulation to shift explicit estimations of short-term time durations. More specifically, it is possible to use an altered metronome coupled with persuasive educational materials to convince young adults with and without ADHD that a second is about 20% slower or faster than it actually is (i.e., 50 or 70 beats per minute as opposed to 60). This belief that a second is slower or faster than reality was associated with productions of short time intervals that conformed to a timing change in the desired direction. When asked to produce a 20-second interval, this manipulation induced interval productions that were scaled up or down according to the direction of the manipulation of the second. In the majority of the young adults tested, this change required only three brief trials with the altered metronome to obtain a stable and durable change in reproduction of the altered timing. This manipulation lasted the length of the study, approximately 45-minutes, even without any warning that there would be another short-term timing estimate at the end of the experimental session.

When participants were asked explicitly if they believed the metronome they heard at the beginning of the study was beating at a true 60 beats per minute, or one beat per second, the majority answered yes. Thus, both behavioral data and subjective report verified that this manipulation was successful in altering belief about the length of a second.

Studies have suggested a primary timing deficit in people with ADHD (e.g., Barkley, et al., 2001; McInerney & Kerns, 2003; Smith et al., 2002; Valko at al., 2010). In the present study, medication status within the ADHD group did appear to have an effect on number of trials required to learn the timing manipulation, with unmedicated participants with ADHD requiring slightly more trials to reach criteria than those on medication, suggesting that medication may be partly compensating for a timing difficulty within the ADHD group. This is inconsistent with at least one other study examining the effects of stimulant medication on time processing that found administration of methylphenidate to children with ADHD did not improve the accuracy of their time interval reproductions (Barkley et al., 1997). A literature search revealed no studies that have examined the effects of medication of timing in adults with ADHD. It should be noted that only four participants within the entire ADHD group required more than three trials to reach criteria, and these four participants were all in the unmedicated group. Due to the limited variance within these two groups with respect to trials required, this finding warrants replication within a larger sample.

Although greater variability in timing has also been found in those with ADHD, in the present study, variability of timing responses (at baseline and during the metronome trials) between the three diagnostic groups did not significantly differ. There may have been an insufficient sample size to reveal much variability: observed power for study aim 1 was sufficient for effects of metronome condition

(observed power=.999), but lower when taking into account diagnostic group by metronome condition over trials (observed power=.286). When variance was examined between the three ADHD status groups for longer time estimations, those evaluating amount of time spent on the delay discounting task and the Matrix Reasoning task, there were again no significant differences. This result is surprising given the numerous studies that have found more variable performance in those with ADHD, especially those not currently on medication (e.g., Castellanos & Tannock, 2002). Results may have looked differently if we were to examine a medication-naïve group of people with ADHD, with those with no medication in their systems over a longer period of time showing greater variance of responses. For the ADHD participants, the amount of time since last taking their medication ranged from several minutes before the study began (for participants who spontaneously reported accidentally taking their medication immediately preceding the study) to about 24 hours, though this information was not formally collected in this study. With the half-life of Adderall, the stimulant medication most often reported by participants in the current study, being approximately four hours depending on body weight, and wash-out time equivalent to approximately five half-lives (Swanson et. al., 1998), there were likely many participants that still had residual medication in their systems. Our sample did include 4 participants with ADHD who were not currently on medication, but this was an underpowered sample size to validly examine any of these effects.

In terms consistent with the Zakay cognitive model of time perception, the metronome manipulation was most likely altering the reference memory that represents of the length of a second. While traditionally this reference memory is referred to as a stable component of the model existing in long-term memory storage, in this study it appears the manipulation was able to override this representation and replace it with a new reference point, at least for short-term time estimations. This new reference point for a second was durable over time as tested in this study and following tasks that did not require the participants explicitly orient to time or maintain the duration of a second. However, the manipulation failed to generalize to longer time periods, an important point that will be discussed.

In the Zakay cognitive model, there are theoretically many ways to directly alter time perception, including speeding up the pacemaker (by increasing arousal), switching on an accumulator (by increasing attention), or by interfering with short term memory consolidation. While many other studies have examined the effects of attention and arousal on timing, this is the first that appears to have attempted to alter the reference point to which comparisons and decisions about timing are made. A literature search fails to find any other studies that have attempted any similar manipulation on the reference memory of any temporal constant. This novel manipulation may be able to be used to study other processes involving timing, such as time management skills and ability to delay gratification.

Time management skills involve evaluations, whether they are conscious or not, of the length of an hour, or a day- all verbal labels we place on amounts of time. These labels are important for individual's decision-making: different factor values must be in place for two people to come to two very different conclusions regarding how much work they believe they may be able to accomplish in an hour, for example. It is not unreasonable that part of this variance could be accounted for by how long that person believes an hour or a day to be. If this were the case, perhaps shifting beliefs of duration of those lengths of time could have an effect on attitudes regarding what could be accomplished in that time. If it is possible to alter the belief of how long a second is, it may be possible to alter the belief of how long an hour is in a similar direct manner.

Although not an explicit aim of the study, it was a hope that the manipulation affecting the length of a second would generalize to longer periods of time. However, it failed to generalize to the two retroactive estimations of longer time durations: the estimations of time spent on the Matrix Reasoning task and the computerized delay discounting task. There are several hypotheses to explain why this may have happened. One possible explanation for this lack of generalization is that different systems are responsible for tracking smaller vs. longer time durations. Indeed, there is evidence (e.g., Meck, Penney, & Pouthas, 2008) that oscillatory dopaminergic activity in the striatum is detected by striatal neurons to discriminate sub-second intervals of timing. However, at longer (i.e., suprasecond) intervals, more cortical

neurons are recruited via cortico-striatal pathways for analyses. In this theory, the striatum is the 'core timer', while timing sense at a suprasecond scale is distributed among coordination of larger-scale neural networks involving greater cortical activation.

Additionally, making retrospective estimations is likely to require a great deal of frontal / cortical activity as evaluations weighing different factors occur. Hence, manipulation of the perception of the length of a second may have affected one system without generalization to the other. Disregarding the metronome manipulation, baseline estimations were not associated with the longer time interval estimations of either the delay discounting task, lending greater evidence to different strategies for long vs. short term estimations.

The amount of variability in explicit timing (i.e., paying specific attention to how much time is passing) is also likely to increase over longer durations. While participants in this study were able to very reliably reproduce small time intervals according to a specified tempo, small mistakes can have a cumulative effect as the interval grows, which would interfere with accurate timing. If the participants were asked to report how many seconds had transpired (rather than minutes) while they were doing the delay discounting task, which lasted an average of 9 minutes (540 seconds), there would doubtlessly be far greater variance in the number of seconds reported due to greater opportunities to lose precision as seconds accumulate.

Another possible explanation for the lack of generalization is the differential nature of the task demands. Although the two longer time interval estimation tasks both required participants to retrospectively estimate the passage of time, the small time scale task involved *producing* an interval. These two different tasks place quite different demands on the participant. The shorter task requires active attention to timing, while the longer task did not require active attention to timing. The time that was passing during the longer time intervals was filled with cognitively-demanding tasks not directly related to time, so ability to precisely monitor and track time was likely limited or perhaps based of a variety of factors other than the perception of the length of a second.

To examine the reasons why the manipulation failed to generalize to longer periods of time, future study could control for differences by equalizing the task demands and manipulating only the durations of time. One way to accomplish this would be to set up an experiment where participants are required to generate small and also longer amounts of time, so that a dissociation point, i.e. a point at which the variability in judgment exceeds accuracy, is revealed. One way to explore the effects of the generative vs. retroactive nature of timing would be to retroactively ask participants to estimate how much time had passed after only a small interval of time. This could be compared with the generative results to examine if the altered timing changed according to type of timing demand, or if the altered timing was consistent within both tasks.

Although the metronome manipulation failed to generalize to longer time periods, it may nevertheless yield some insight into timing processes and cognitive models that attempt to explain them. Timing production tasks are used quite frequently in studies that examine people's sense of time, and the ease with which the present study was able to manipulate the perception of the seconds that underlie the production shows that the reference memory of a second perhaps should not be thought of as a constant factor. In the Zakay model there are no variables that feed into or influence the reference memory, suggesting that it is stable and constant. However, again given the ease with which it was shifted in this study, perhaps this model needs to be expanded to include factors that may affect the reference memory.

The metronome manipulation also failed to affect delay discounting rates. Delay discounting is a complex phenomenon that is the end result of many cognitive processes. Although some evaluation or timing processing must be playing a role in delay discounting, as nearly everyone would prefer $100 today rather than $100 tomorrow, it may simply be that the sum of the other high-level cognitive processes outweigh the contributions the variable of perception of length of a second may be adding.

This may be the result of the manipulation failing to generalize to longer periods of time, as the task had people make decisions on time scales of days rather than seconds. Hyperbolic delay discounting curves have been observed when

intertemporal intervals are as short as seconds, though they are less steep than the curves observed for longer-term discounting studies. A future study could examine delay discounting rates as affected by the metronome manipulation over much shorter periods of time, on a scale of seconds rather than days to avoid the confounding issue of longer term generalization. Imaging studies support that different systems may be accounting for the different steepness of discounting: during discounting tasks on smaller time scales, greater striatal activation has been observed in imaging studies, as opposed to more orbitofrontal activation found in longer-term discounting tasks (Gregorios-Pippas et al., 2009).

In the present study, no variables collected were found to be related to delay discounting rates, including impulsivity, ADHD / medication status, hyperactivity and inattentive symptoms, processing speed, and working memory. That impulsivity was not related to delay discounting rates in this study was somewhat surprising, as preference for sooner rewards over delayed rewards would seem to tap into at least some aspect of impulsivity. At least one previous study by Swann et al. (2002) found that delay discounting was related with high impulsivity on the BIS-11, but this finding was not replicated in any subsequent studies. The nonplanning subscale of the BIS-11 was found to correlate with delay discounting by de Wit et al. (2007), but this finding also failed to replicate within any sample under study here. The current sample was comprised almost entirely of students, and even those without ADHD reported higher levels of impulsivity on the BIS-11 than the means for the above

studies. However, the mean age for the de Wit study was 45 years and 40 for the Swann study, whereas for the current study mean age was 19. It may be that high impulsivity in middle aged people is developmentally less common and qualitatively different than high impulsivity in younger people.

The current sample of students were also in general showing steeper discounting rates than the adult populations many of these studies used: the mean *k* for our control sample was .039 while for the normative adult population in the literature a mean *k* value of .013 is generally reported (Kable & Glimcher, 2007; Kirby, Petry, & Bickel, 1999; Monterosso et al., 2007). The set of controls in this study also reported more ADHD symptoms on the ASRS than the normative population. It could be that the relationship between delay discounting and impulsivity is different in this set of higher-discounting, more impulsive normative controls than in a set of lower-discounting, less impulsive normative controls. Additionally, as many studies using this delay discounting measure tend to examine preferences in substance abuse populations, their control samples tended to be older and not as educated as the current sample. Another possibility is that the explicit orientation to time via the manipulation may have caused participants to orient their attention specifically to the passage of time, which may have altered their behavioral choices.

ADHD status and medication status within the ADHD group also did not affect rates of delay discounting in the current study. This is inconsistent with

previous findings. Scheres, Lee, and Sumiya (2008) found that people with ADHD that exhibit higher impulsivity exhibit especially steep delay-discounting curves. Sheils et al. (2009) duplicated this finding, and showed that *k* decreased within their participant sample with ADHD with the administration of stimulant medication. This was not the case with our sample, with neither ADHD status, impulsivity, nor current medication status contributing significantly, in any combination, to *k*. However, our study was not a repeated-measures design with and without medication, and residual medication effects may have remained in those classified as "off medication". Also, the lack of actual monetary rewards and use of hypothetical rewards may have weakened possible relationships: the Scheres, Lee & Sumiya 2008 study found that real temporal discounting tasks are more sensitive to ADHD-related delay aversion than hypothetical tasks.

Neither the processing speed measures nor the working memory measures were associated with *k*. While the ADHD group showed clear differences on several of these measures when compared with the non-ADHD group, none of these measures were correlated with *k*. The reason for this lack of relationship is not clear, but one possible explanation is that neither working memory nor processing speed are critical components of delay discounting, a highly complex decision making task. Additionally, our rather homogenous group of undergraduates may not have exhibited the variability in performance on these measures necessary to reveal any impact these traits may have on delay discounting.

Among the main four cognitive measures, none were associated with accuracy of time estimations. However, disregarding accuracy of estimation, it was found that total score on digit span was correlated with the actual value of baseline time estimations of 20 seconds, as well as estimation of time spent on the Matrix Reasoning task. Participants who achieved lower total scores on digit span tended to produce contracted 20-second intervals (i.e., they said "stop" when less than 20 seconds had gone by). In contrast, participants with higher scores on digit span tended to produce expanded 20-second intervals (i.e., they said "stop" when more than 20 seconds had gone by). Those with better working memory, of which simple attention is a component, may have higher distress tolerance for longer periods of "empty" time before declaring time is up than those with poorer attention and working memory.

Digit span total score was also positively correlated with estimation of time spent on the Matrix Reasoning task. One confounding factor of this relationship is the correlation between Matrix Reasoning score and Digit Span score ($r(75)=.274$, $p=.017$), and that those who did better on Matrix Reasoning completed more items and tended to take longer, so their estimations would likely to be longer. Though a partial correlation found that Matrix Reasoning raw score was accounting for this correlation, it may be that this partial correlation was removing some of the working memory variance as well. More difficult items on the Matrix Reasoning task place demands on working memory to hold and manipulate information, especially when

looking for more complex patterns. Thus, working memory may still be an important component of these temporal estimations. However, the N-Back task, which also taps into working memory, was not correlated with baseline time estimations or Matrix Reasoning duration estimations, which is surprising as performance on the N-back task *was* found to be significantly correlated with digit span performance.

There are several ways these tasks diverge. One way is that digit span and the time estimation tasks require a verbal response and attention to auditory stimuli, whereas the N-back task does not incorporate auditory information and does not require a verbal response. The N-back task is characterized by a single, continuous demand over 100 trials. Contrastingly, digit span has three separate subtasks with different, increasingly difficult demands built into it. Digit span total score is the sum of digits forward, digits back, and digits sequenced, and so is a mixed index that lumps together simple and more complex attention with working memory. It also becomes more difficult until a performance ceiling is reached, whereas the difficulty of the N-back task does not change over time. Perhaps the multidimensionality of digit span was more suited to capture the more complex process of time judgment. Though results of the current study present two pieces of converging evidence to suggest digit span performance may be related to time estimation, the correlations are small to medium and require replication.

Limitations & Future Directions.

As discussed previously, though the sample sizes within each metronome condition were sufficient, there was insufficient power to examine interactions if any were present among the three diagnostic groups over repeated trials. Additionally, the study was completed without an initial goal of separating the participants with ADHD into different groups depending on medication status, and thus sample sizes were not large enough to properly assess the role medication may have been playing in these results. Rather than a cross-sectional study, a repeated measures on-medication/off-medication would better examine this question. Finally, the study sample had higher rates of discounting than observed in other studies, which may have been related to higher impulsivity, though the nature of this relationship was not clear in this study. Future study in these areas may include more clinically-impaired populations from a wider age group with a wider range of educational and current occupational status.

Overall, it would be important for future studies to include a mechanism for examining the point at which the manipulation that alters perceptions of small amounts of time fails to translate to longer amount of time. To better understand how the manipulation may be affecting time perception, other measures of short-term time estimations could be taken that incorporate not only producing time intervals, but also judging time intervals and comparing various time intervals. Additionally, given that delay discounting is such a complex construct, examining

other potential factors that may enter into the decision-making process such as attitudes toward time passage and current financial status of the individual would be worthwhile to study.

In sum, the current study has established a novel technique to alter explicit time judgments on a seconds-scale, though this alteration does not appear to affect delay discounting, perhaps because it failed to generalize to longer periods of time. Delay discounting remains a complex phenomenon whose underlying cognitive processes are mostly unknown. Further investigation, possibly incorporating some of the studies proposed above, is warranted to clarify the relationship that may exist between sense of time, impulsivity, cognitive processes, and delay discounting.

Appendix A

Demographic Questionnaire

1. Gender (please circle one): Male Female Other_____

2. Age: _____

3. Have you ever been diagnosed with Attention Deficit / Hyperactivity Disorder? Circle one:

No

Yes (if so, when? _____)

4. Do you take medication for ADHD? (please circle one) Yes No

4a: if yes, what is the name and daily dosage of the medication?

_____

5. Did you take ADHD medication today? (please circle one) Yes No

Appendix B: Sham Educational Material

The Importance of Accurate Timing

An accurate sense of time has been linked with higher IQ (Christianson et al., 2009), greater average annual salary (The Center for Temporal Perception and Studies, 2010), and higher self-reported happiness and life satisfaction (Lymberos, Brown, & Aunchman, 2010). Though we all have some sense of time, most people have never received explicit training in this area. Thus, one goal of the present study is to see if a more accurate sense of timing can be taught to people that may not have previously received formal timing education.

You will be provided with a metronome that ticks off at 60 ticks per minute (1 per second) and asked to tap along with the beat. Following this, you will be asked to indicate when you think a certain amount of time has passed. You will continue to receive this timing training several times to help us understand how people learn how to accurately judge time intervals.

Appendix C: BIS-11

DIRECTIONS: People differ in the ways they act and think in different situations. This is a test to measure some of the ways in which you act and think. Read each statement and put an X on the appropriate circle on the right side of this page. Do not spend too much time on any statement. Answer quickly and honestly.

	O	O	O	O
	Rarely/Never	Occasionally	Often	Almost Always/Always
1 I plan tasks carefully.	O	O	O	O
2 I do things without thinking.	O	O	O	O
3 I make-up my mind quickly.	O	O	O	O
4 I am happy-go-lucky.	O	O	O	O
5 I don't "pay attention."	O	O	O	O
6 I have "racing" thoughts.	O	O	O	O
7 I plan trips well ahead of time.	O	O	O	O
8 I am self controlled.	O	O	O	O
9 I concentrate easily.	O	O	O	O
10 I save regularly.	O	O	O	O
11 I "squirm" at plays or lectures.	O	O	O	O
12 I am a careful thinker.	O	O	O	O
13 I plan for job security.	O	O	O	O
14 I say things without thinking.	O	O	O	O
15 I like to think about complex problems.	O	O	O	O
16 I change jobs.	O	O	O	O
17 I act "on impulse."	O	O	O	O
18 I get easily bored when solving thought problems.	O	O	O	O
19 I act on the spur of the moment.	O	O	O	O
20 I am a steady thinker.	O	O	O	O
21 I change residences.	O	O	O	O
22 I buy things on impulse.	O	O	O	O
23 I can only think about one thing at a time.	O	O	O	O
24 I change hobbies.	O	O	O	O
25 I spend or charge more than I earn.	O	O	O	O
26 I often have extraneous thoughts when thinking.	O	O	O	O
27 I am more interested in the present than the future.	O	O	O	O
28 I am restless at the theater or lectures.	O	O	O	O
29 I like puzzles.	O	O	O	O
30 I am future oriented.	O	O	O	O

Appendix D: Adult Self-Report Scale Symptom Checklist (ASRS)

Adult Self-Report Scale (ASRS) Symptom Checklist

Patient Name		Today's Date					
Please answer the questions below, rating yourself on each of the criteria shown using the scale on the right side of the page. As you answer each question, circle the correct number that best describes how you have felt and conducted yourself over the past 6 months. Please give this completed checklist to your healthcare professional to discuss during today's appointment.	Never	Rarely	Sometimes	Often	Very Often	Score
1. How often do you make careless mistakes when you have to work on a boring or difficult project?	0	1	2	3	4	
2. How often do you have difficulty keeping your attention when you are doing boring or repetitive work?	0	1	2	3	4	
3. How often do you have difficulty concentrating on what people say to you, even when they are speaking to you directly?	0	1	2	3	4	
4. How often do you have trouble wrapping up the final details of a project, once the challenging parts have been done?	0	1	2	3	4	
5. How often do you have difficulty getting things in order when you have to do a task that requires organization?	0	1	2	3	4	
6. When you have a task that requires a lot of thought, how often do you avoid or delay getting started?	0	1	2	3	4	
7. How often do you misplace or have difficulty finding things at home or at work?	0	1	2	3	4	
8. How often are you distracted by activity or noise around you?	0	1	2	3	4	
9. How often do you have problems remembering appointments or obligations?	0	1	2	3	4	
					Part A – Total	
10. How often do you fidget or squirm with your hands or feet when you have to sit down for a long time?	0	1	2	3	4	
11. How often do you leave your seat in meetings or other situations in which you are expected to remain seated?	0	1	2	3	4	
12. How often do you feel restless or fidgety?	0	1	2	3	4	
13. How often do you have difficulty unwinding and relaxing when you have time to yourself?	0	1	2	3	4	
14. How often do you feel overly active and compelled to do things, like you were driven by a motor?	0	1	2	3	4	
15. How often do you find yourself talking too much when you are in social situations?	0	1	2	3	4	
16. When you're in a conversation, how often do you find yourself finishing the sentences of the people you are talking to, before they can finish them themselves?	0	1	2	3	4	
17. How often do you have difficulty waiting your turn in situations when turn taking is required?	0	1	2	3	4	
18. How often do you interrupt others when they are busy?	0	1	2	3	4	
					Part B – Total	

Appendix E: Manipulation Check / Debriefing Form

Timing Questions

Looking back, to what degree did you believe the time interval you were trained on was accurate to one beat per second? Circle one choice.

1. Definitely thought it was **not** accurate.

2. Thought it was probably **not** accurate, but could be accurate.

3. Thought the chances of it being accurate or not accurate were 50/50.

4. Thought it was possibly not accurate, but definitely could be accurate.

5. Definitely thought it was accurate (60 beats per minute).

Any comments to add about this study? Use the space below. Thanks!

Debriefing Form

In the informed consent document you read and signed before the study began, you were told the purpose of this study was "to examine the relationship between sense of time and decision making in a computerized task." The real purpose of this study is to examine how believing a second is either slower or faster than it really is affects that decision making task. The metronome you listened to and tapped along with was not beating at 60 beats per minute like you were told; it was actually beating at either 50 beats per minute or 70 beats per minute.

We could not tell you the real purpose of the study in case that would have changed your answers or how you acted.

Now that you have been told the real purpose of this study, we want to make sure we still have your permission to use your data. Remember, we want to understand how people act in general. We will never draw any results about you personally. If you do

not want your data included, your refusal will not impact current or future relationships with The University of Texas at Austin. It will also not affect any compensation you were promised at the start of the study.

Now that you know the real purpose of the study, please do not tell other students until after the term is over. We do not want this detail to influence future volunteers.

Your signature below means that you understand the real purpose of the study. Your signature does not constitute a waiver of any legal rights.

Please indicate if you do or do not agree for us to use your data now that you know the real purpose of the study.

CHECK ONE:

___ I understand the real purpose of the study and allow the researchers to use my data.

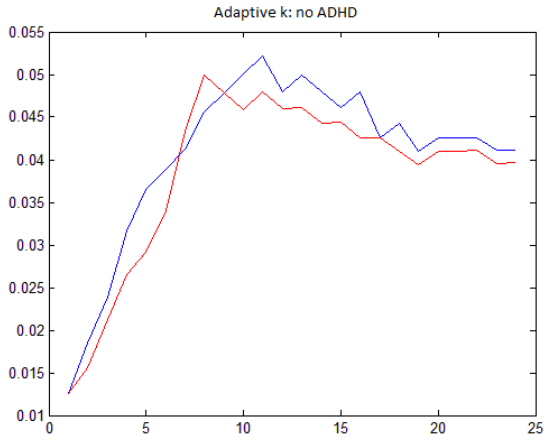
___ I understand the real purpose of the study and do NOT allow the researchers to use my data."

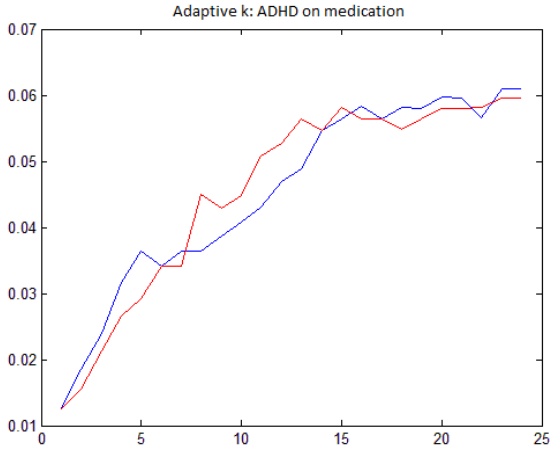
Signature of Subject Date

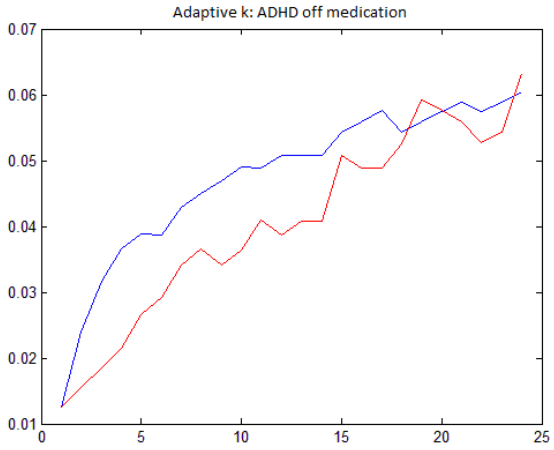
Signature of Research Staff who debriefed subject
Date

If you want more information about this study, you can talk to any of the investigators: Rachel Berman, rachel.berman@mail.utexas.edu, 617-244-8885; or David Tucker, dtucker@mail.utexas.edu. If you would like to talk about this study with someone not involved in the study, you can talk to The University of Texas at Austin Institutional Review Board for the Protection of Human Subjects at (512) 471-8871. If you ask, we will protect your identity to the extent possible. You can also send an email to orsc@uts.cc.utexas.edu or a letter to IRB Administrator, P.O. Box 7426, Mail Code A 3200, Austin, TX 78713.

Appendix F: Adaptive *k* by diagnostic group and metronome status over trials in delay discounting task (red: slow metronome; blue: fast metronome)







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